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# S-191 SENSOR PERFORMANCE EVALUATION

## FINAL REPORT

Job Order 75-215

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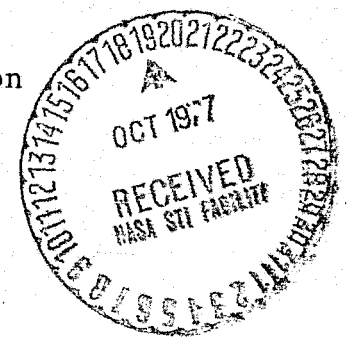
Prepared By

Lockheed Electronics Company, Inc.
Aerospace Systems Division
Houston, Texas

Contract NAS 9-12200

for

Earth Observations Division






*National Aeronautics and Space Administration*

***LYNDON B. JOHNSON SPACE CENTER***

***Houston, Texas***

June 1975

LEC-5778

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PREPARED BY

C. L. Hughes, Principal Engineer
Exploratory Investigations Section

APPROVED BY

J. J. Carney, Supervisor
Exploratory Investigations Section

O. N. Brandt, Acting Manager
E. O. Exploratory Studies Department

Prepared By

Lockheed Electronics Company, Inc.

For

Earth Observations Division

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

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## DEFINITION OF TERMS

| | |
|---|---|
| DOY | Numerical day of year during EREP operation (May 1973 through February 1974). An example of this relationship which exists between EREP DOY 165 and the Gregorian calendar is June 14, 1973. There is no redundancy in the EREP numbering system; however, there may be confusion in the chronological order; for instance lower number DOY's from 001 through 032 refer to 1974, while higher DOY numbers refer to 1973. |
| ECLIPTIC | The plane defined by the earth's orbit about the sun. |
| EREP | Earth Resources Experiment Package |
| Kp | K-index is a measure of transient geomagnetic activity recorded by earth observatory magnetometers over a three hour range. The index varies from 0 to 9, with $K = 0$ indicating quiet or calm, while $K = 9$ signifies great geomagnetic fluctuations. The K-index from several observations are combined to form a worldwide, or planetary index, Kp. |
| LUMINANCE LONGITUDE | The angle of observation (reflection angle) projected into the phase plane. (From figures 3 and 5 in section 3.4 of ref. 3.) |
| PHASE ANGLE | In this report, the included angle described by two imaginary lines intersecting at the center of the moon, one passing through the center of the sun and the other through the point of observation. |

| | |
|---|---|
| SELENOGRAPHY | The science dealing with the moon, especially with reference to its physical features. |
| VTS | The S-191 Viewfinder Tracking System which was optically boresighted to the S-191 spectrometer and allowed the astronaut operator to view and track targets from space. The VTS target scene was recorded on 16 mm movie film cycled at one-half second intervals for use in identifying precise spectrometer pointing directions. |

# S-191 SENSOR PERFORMANCE EVALUATION
# FINAL REPORT

## 1.0 INTRODUCTION

A final analysis has been performed on the Skylab S-191 spectrometer data received from missions SL-2, SL-3, and SL-4. This analysis follows the plan put forth in LEC-0413-5 on an Instrumentation Plan for S-191 System Spectroradiometric Response Determination (SPE-S-191-005).

The purpose of this task was to determine the repeatability and accuracy of the S-191 spectroradiometric internal calibration by correlation to the output obtained from well-defined external targets. These included targets on the moon and earth as well as deep space. In addition, the accuracy of the S-191 short wavelength auto calibration was flight checked by correlation of the EREP S-191 outputs and the Backup Unit S-191 outputs after viewing selected targets on the moon.

The analysis is divided into two sections because of general dissimilarities in the data; short wavelength (SWL) and long wavelength (LWL).

## 2.0 SWL ANALYSIS

The SWL analysis was first accomplished by comparing the outputs from several lunar data takes both from the EREP S-191 and the Backup Unit S-191. In addition, the EREP S-191 lunar outputs from different lunations were intercompared in order to establish the relative accuracy and to determine if any drift and/or degradation had occured in the instrument. Finally, the lunar spectral data was compared to relative data in the literature and some preliminary off-band corrections were made.

### 2.1 COMPARISON OF DATA FROM EREP S-191 AND THE BACKUP UNIT S-191

During the months of November 1973 through March 1974, the Backup Unit S-191 was operated during appropriate periods of several lunations in conjunction with the EREP S-191 to obtain data from three Mare areas on the moon. This Backup Unit data was collected primarily at Mt. Capulin, New Mexico and Denver, Colorado. The reason for collecting the backup unit data was that there had been some question as to the pre-flight SWL calibration of the EREP S-191. Because of this, it was desired to intercompare their outputs on a common target to gain additional confidence in the flight unit's calibration.

The results of the backup unit data taken is contained in the final report of MSC-05548 (ref. 1). In this report, the phase angle* versus radiance at several different wavelengths

*See Definition of Terms, page vi.

was developed for Mare Serenetatis, Mare Tranquillitatis, and Mare Imbrium. An illustration of the location of the Mares and the approximate field of view of S-191 superimposed on them is shown in figure 1. This data was not individually solar irradiance corrected† but most of the data was collected in November 1973, December 1973, and January 1974 which is very close to minimum solar distance and is considered equivalent to EREP* data taken on January 7, 1974.

Lunar data was collected from six EREP passes. However, only four will be used in the following analysis. LC-2 (Lunar Calibration-2) did not have correlating photography and LC-6 was a special data taken close to full moon where radiance versus phase angle is a highly non-linear function.

The four lunar data times and locations, the lunar phase angles*, and solar irradiance correction† factors are shown in table I.

Seven scans were usually averaged for generation of the data on each Mare if all scans within the time span were good. All radiance data was solar distance normalized to DOY 007* (Day of Year 007) for comparison to the S-191 Backup Unit data.

The comparisons for Mare Serenetatis and Mare Tranquillitatis are shown in figures 2, 3, 4, 5, 6, 7, 8, and 9. The results of this comparison are very good for Mare Serenetatis

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†Solar irradiance correction refers to the calculation of the difference in irradiance at the lunar surface as caused by seasonal variations in the solar distance. See reference 2 for basis of this calculation.

*See Definition of Terms, page vi.

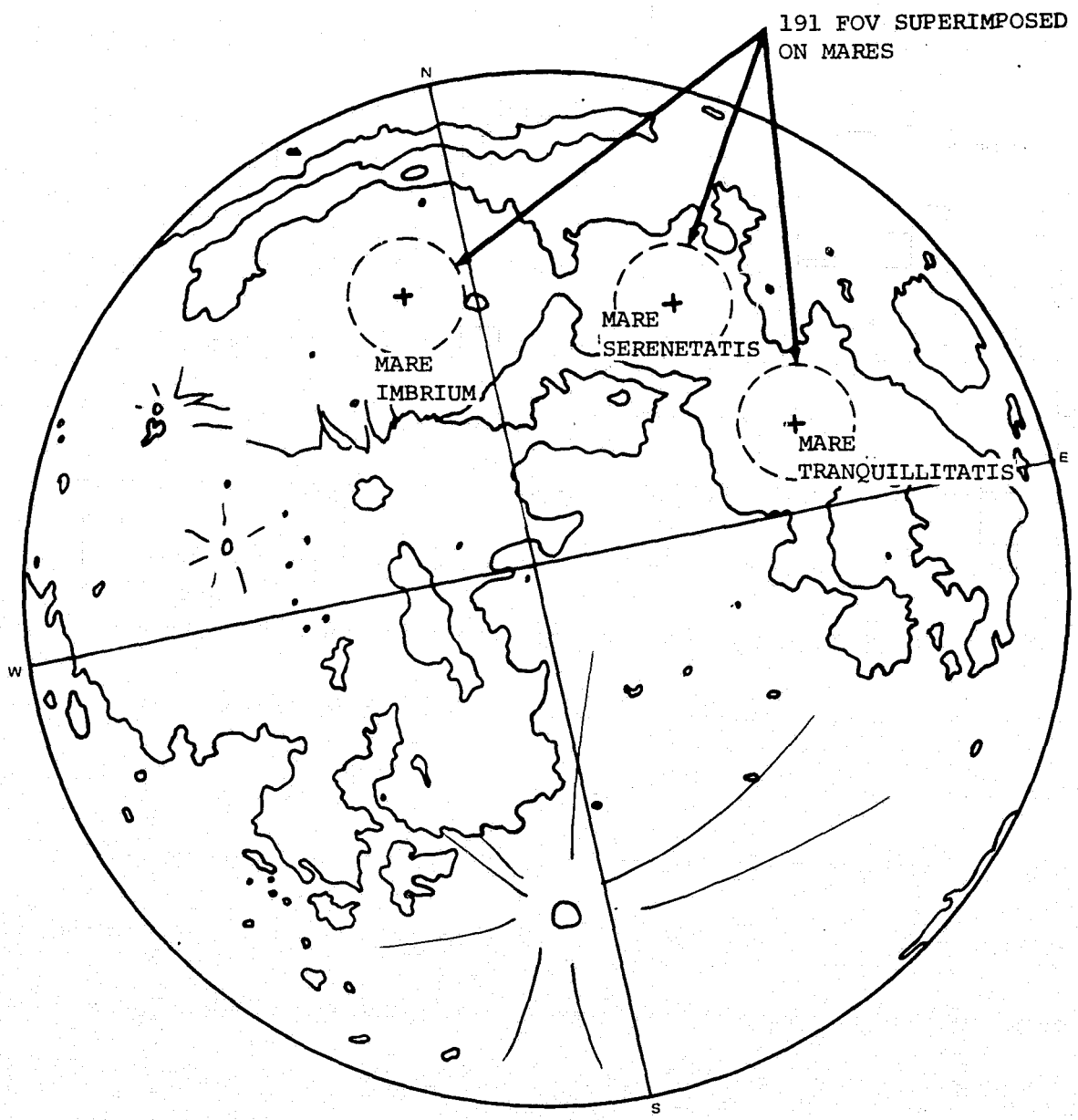



Figure 1.– Location of Mares used in the S-191 lunar calibration.

TABLE 1. — S-191 EREP LUNAR DATA IDENTIFICATION

| Nomenclature/Mission | Mare Serenetatis | | Mare Tranquillitatis | | Phase angle $\phi$ in degrees | Relative solar irradiance factor |
|---|---|---|---|---|---|---|
| | Start | Stop | Start | Stop | | |
| LC-1/SL-2 | 165:15:42:24.05 | 165:15:42:30.616 | 165:15:41:48.48 | 165:15:41:55.02 | -12.92 | 1.0666 |
| LC-3/SL-3 | 254:13:58:8.17 | 254:13:58:14.68 | 254:13:57:41.22 | 254:13:57:47.73 | -13.60 | 1.0457 |
| LC-4/SL-4 | 343:00:25:52.48 | 343:00:25:58.98 | 343:00:25:36.70 | 343:00:25:42.27 | -14.77 | 1.0032 |
| LC-5/SL-4 | 007:13:09:02.77 | 007:13:09:09.26 | 007:13:08:43.29 | 007:13:08:49.78 | -13.45 | 1.0000 |

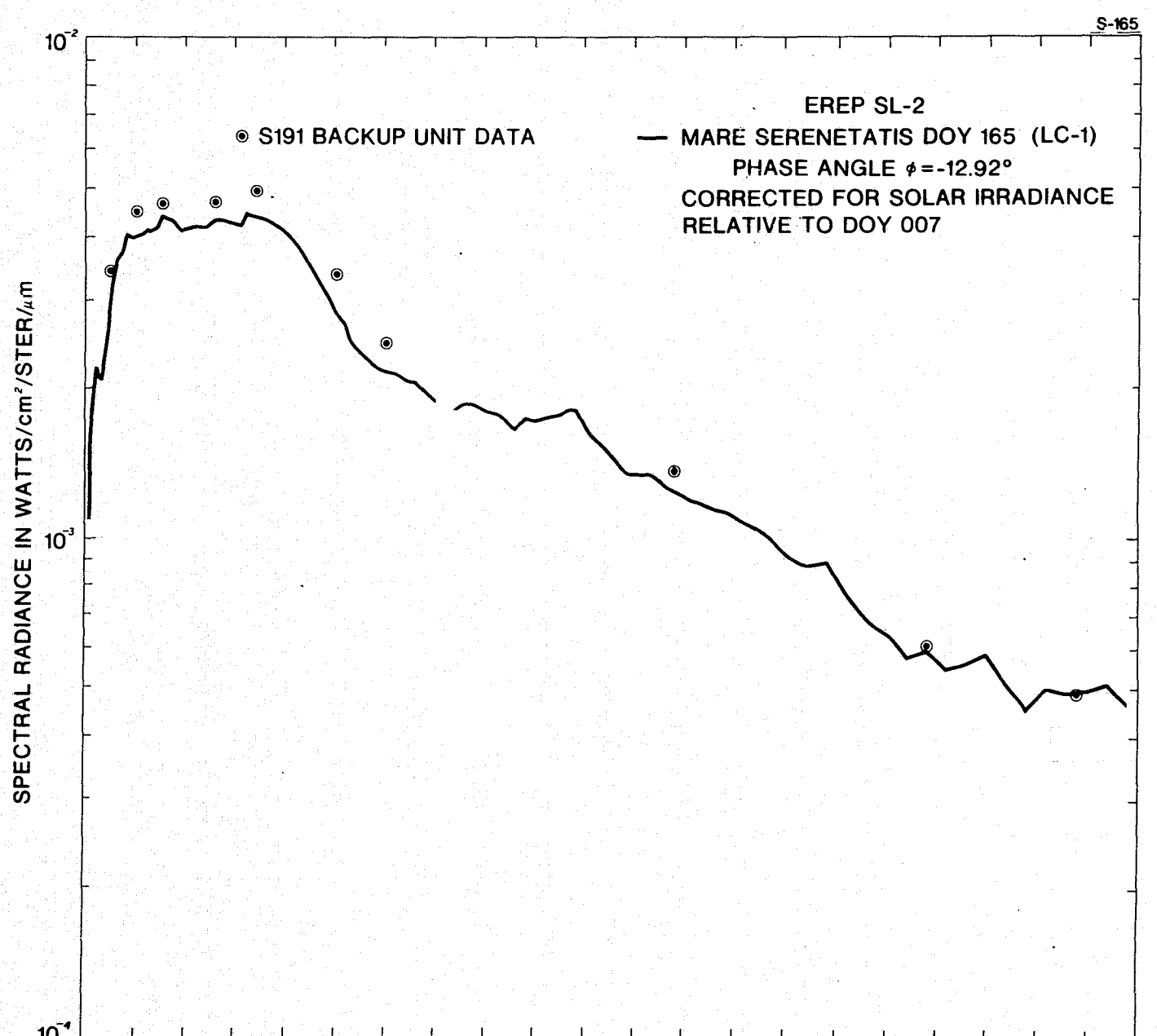



Figure 2.— Mare Serenetatis DOY 165 (LC-1).

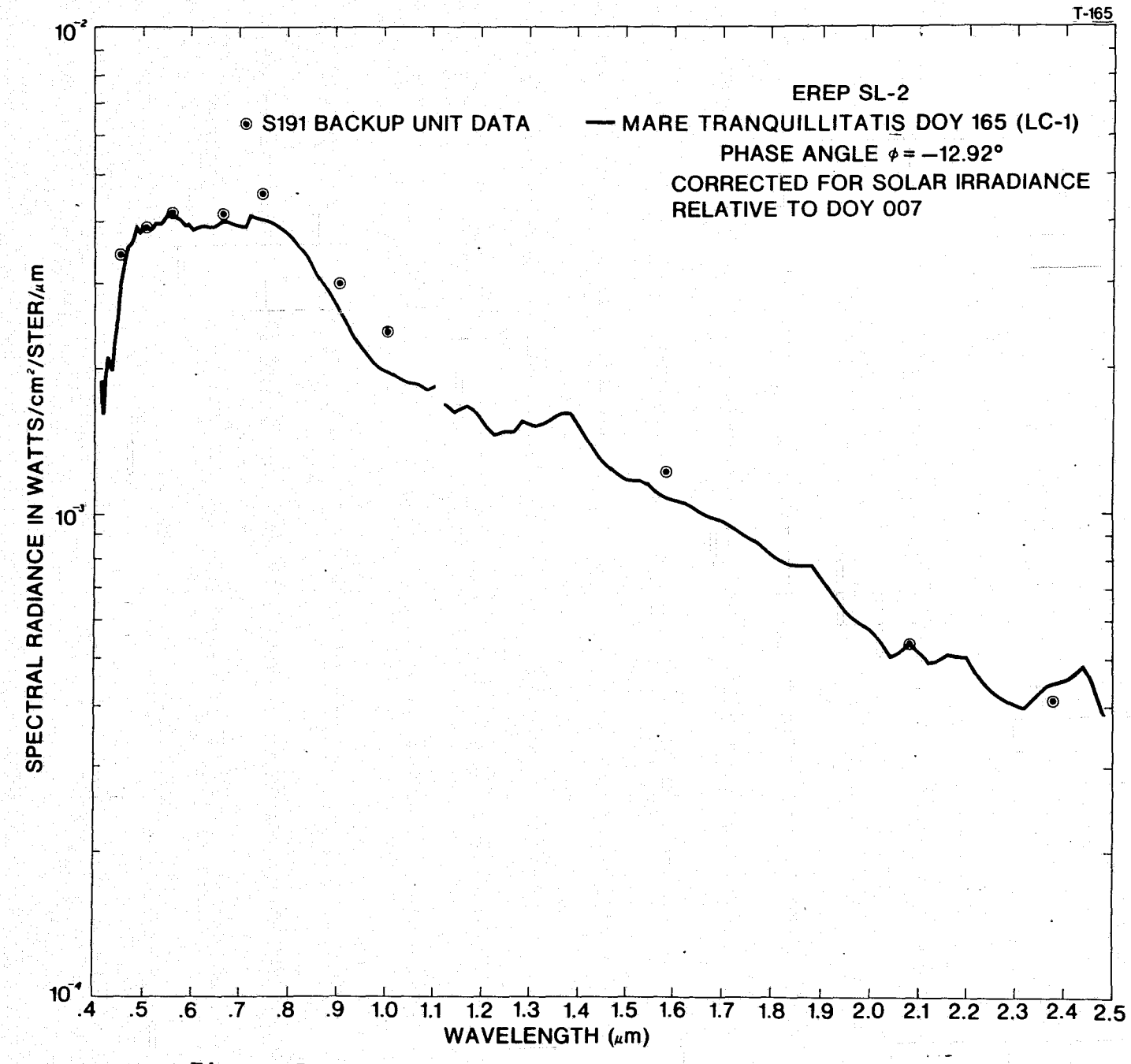



Figure 3.– Mare Tranquillitatis DOY 165 (LC-1).

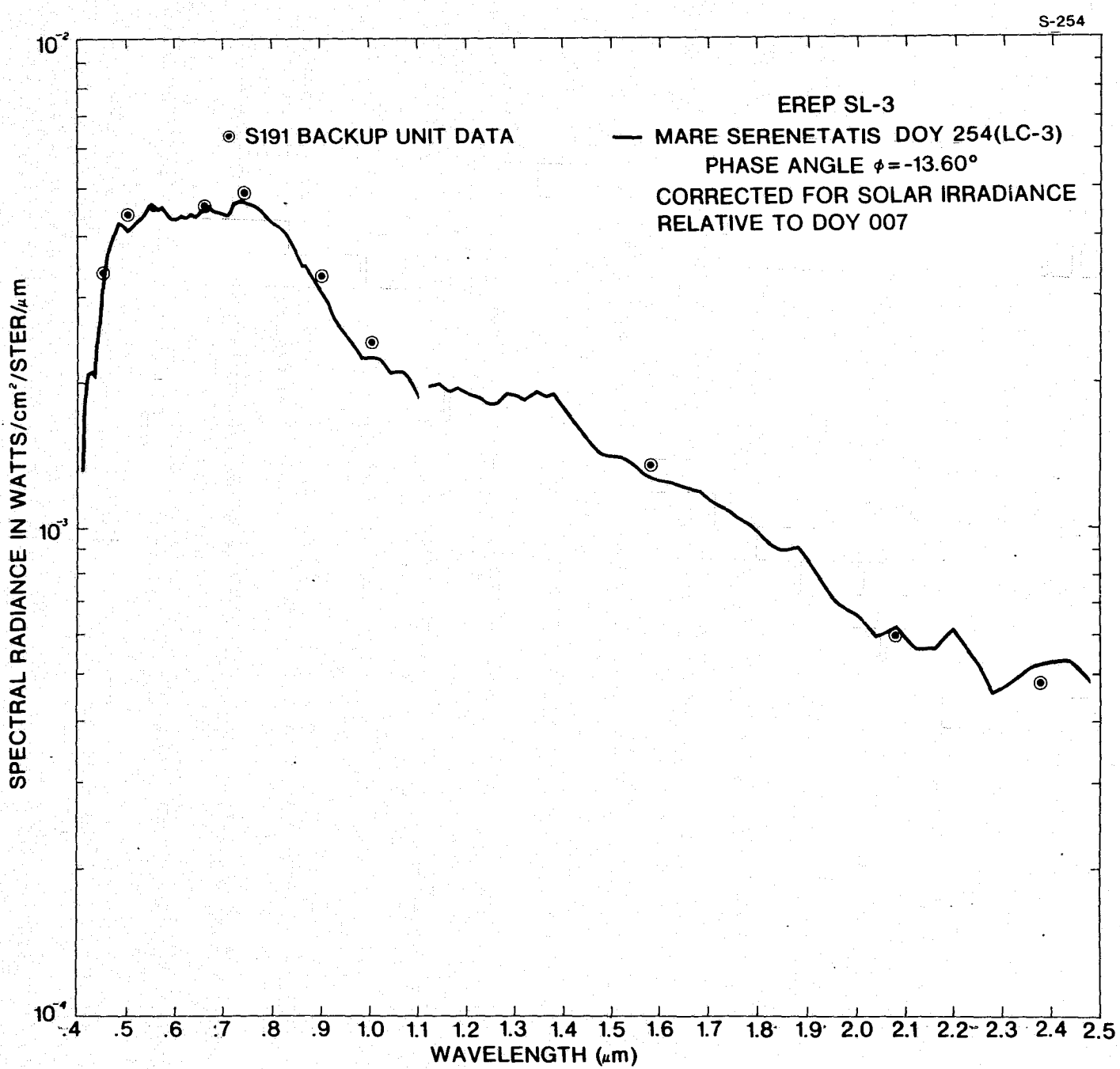



Figure 4.– Mare Serenetatis DOY 254 (LC-3).

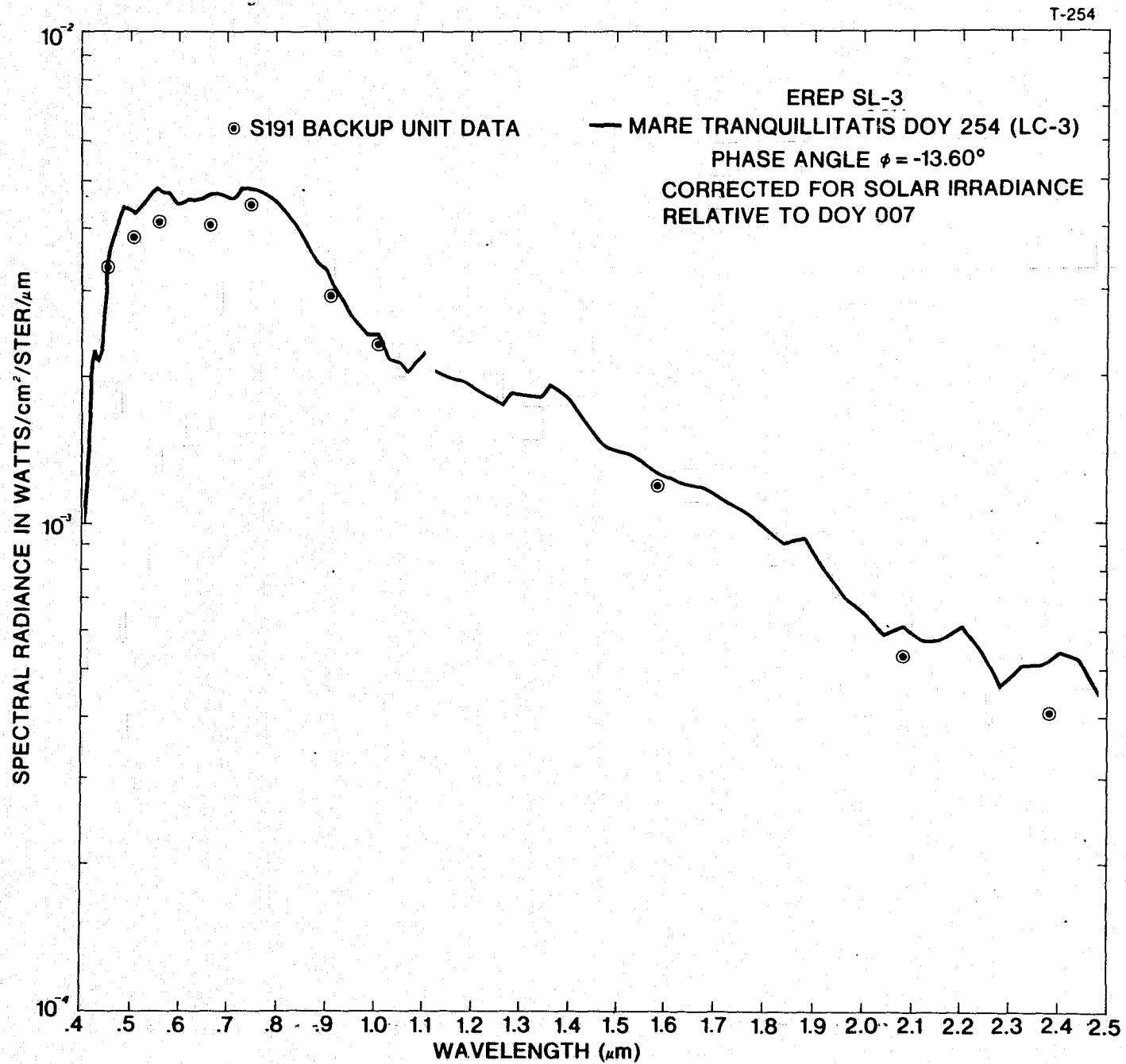



Figure 5.— Mare Tranquillitatis DOY 254 (LC-3).

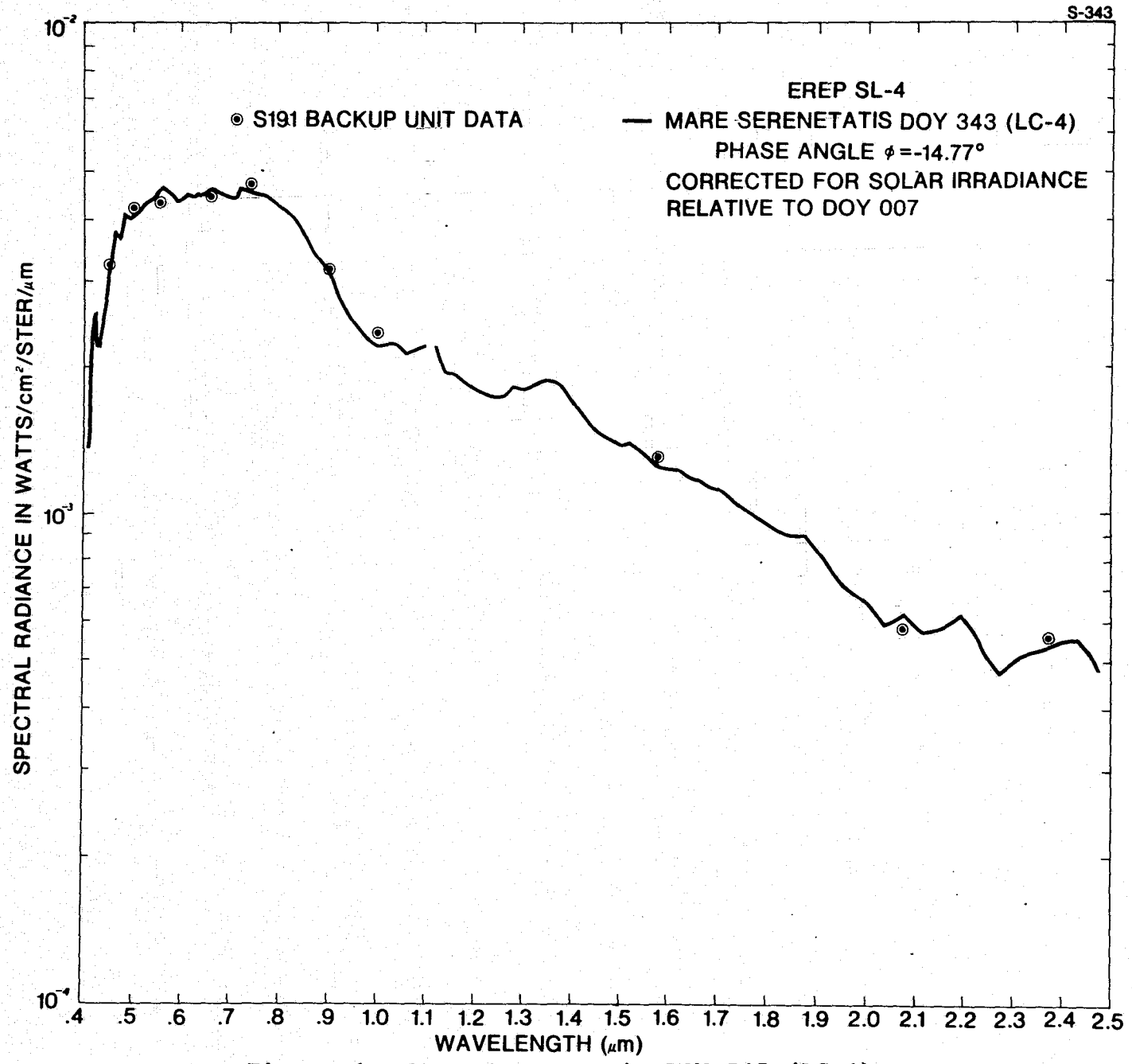



Figure 6.— Mare Serenetatis DOY 343 (LC-4).

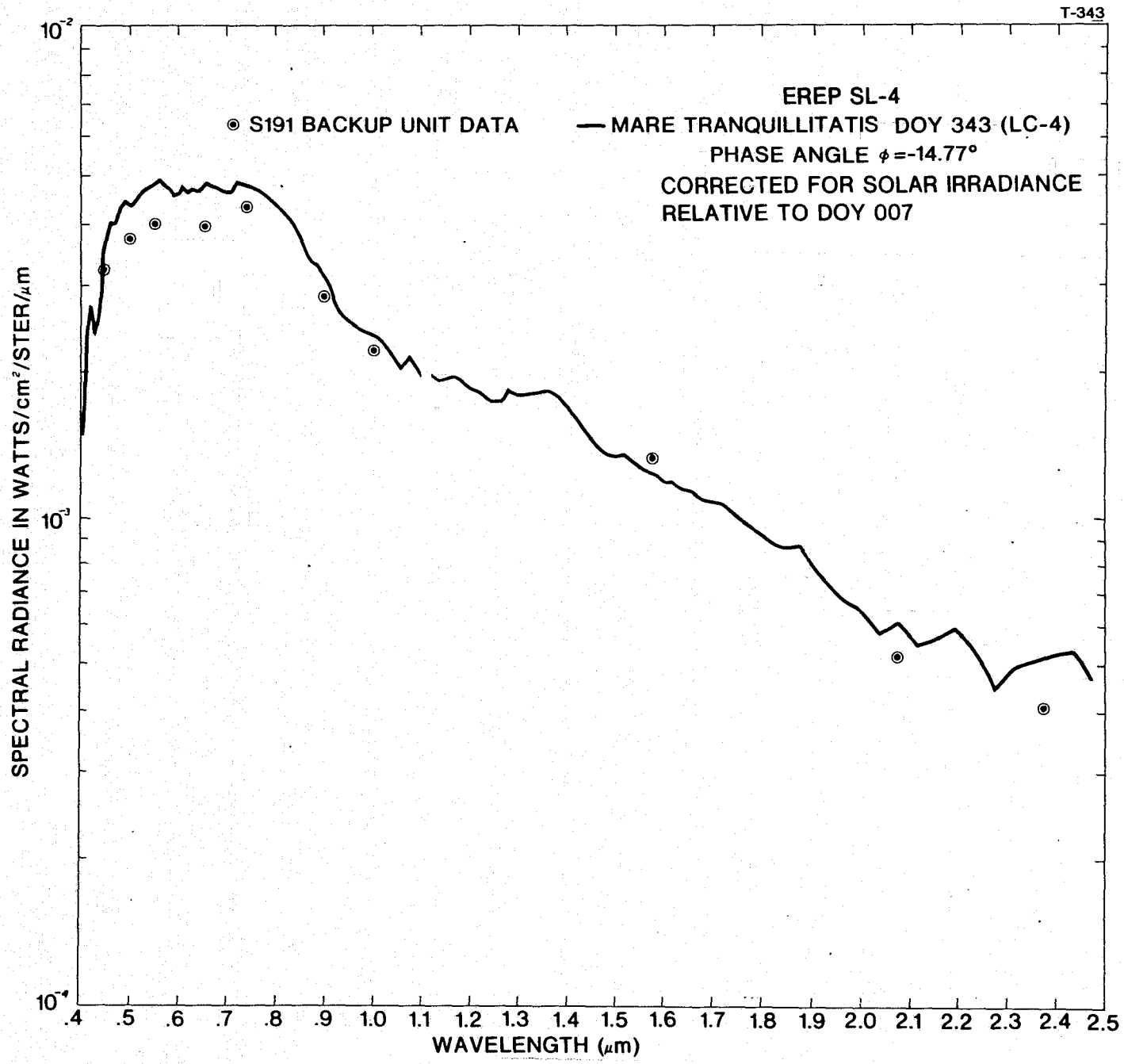



Figure 7.– Mare Tranquillitatis DOY 343 (LC-4).

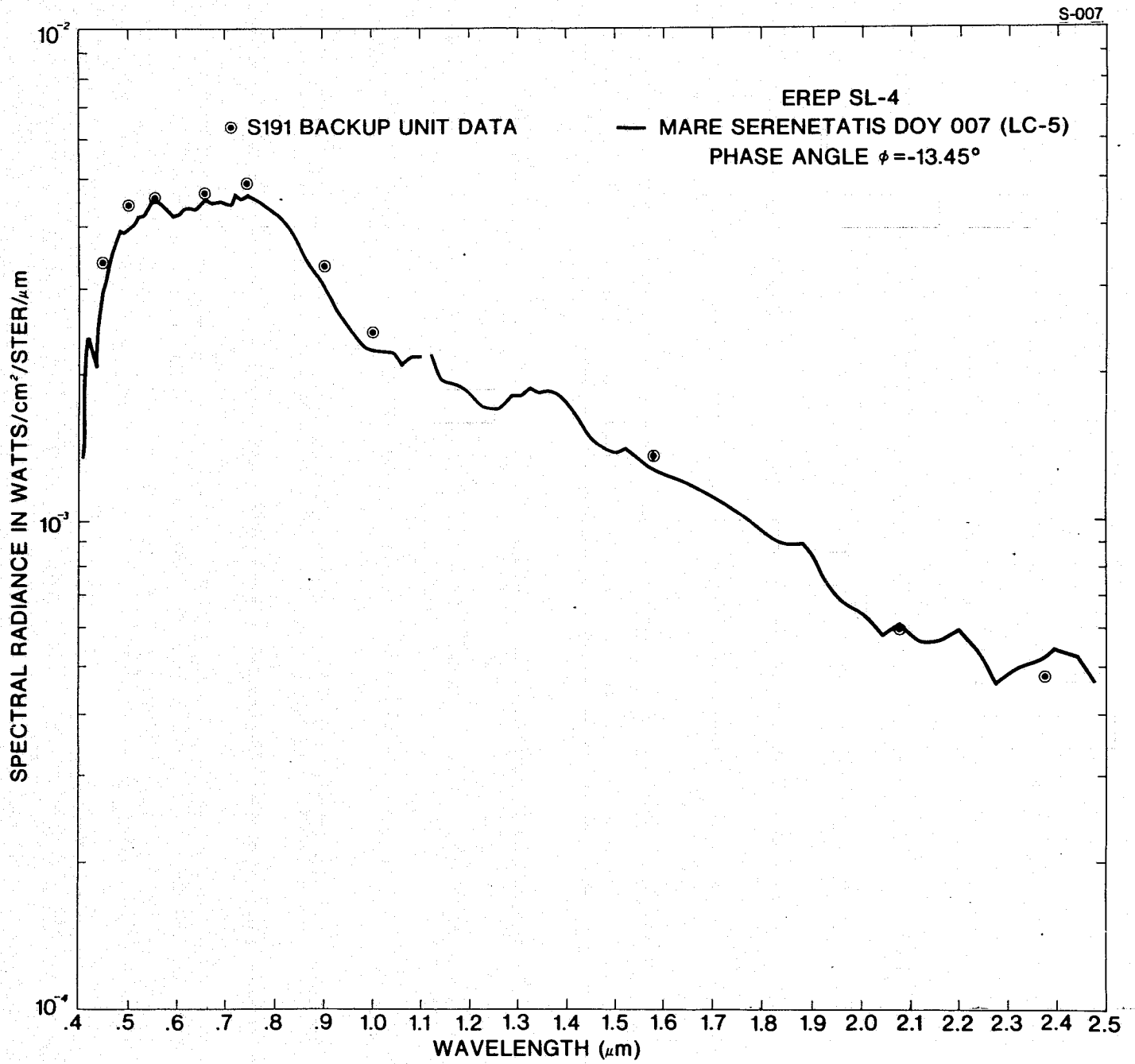



Figure 8.– Mare Serenetatis DOY 007 (LC-5).

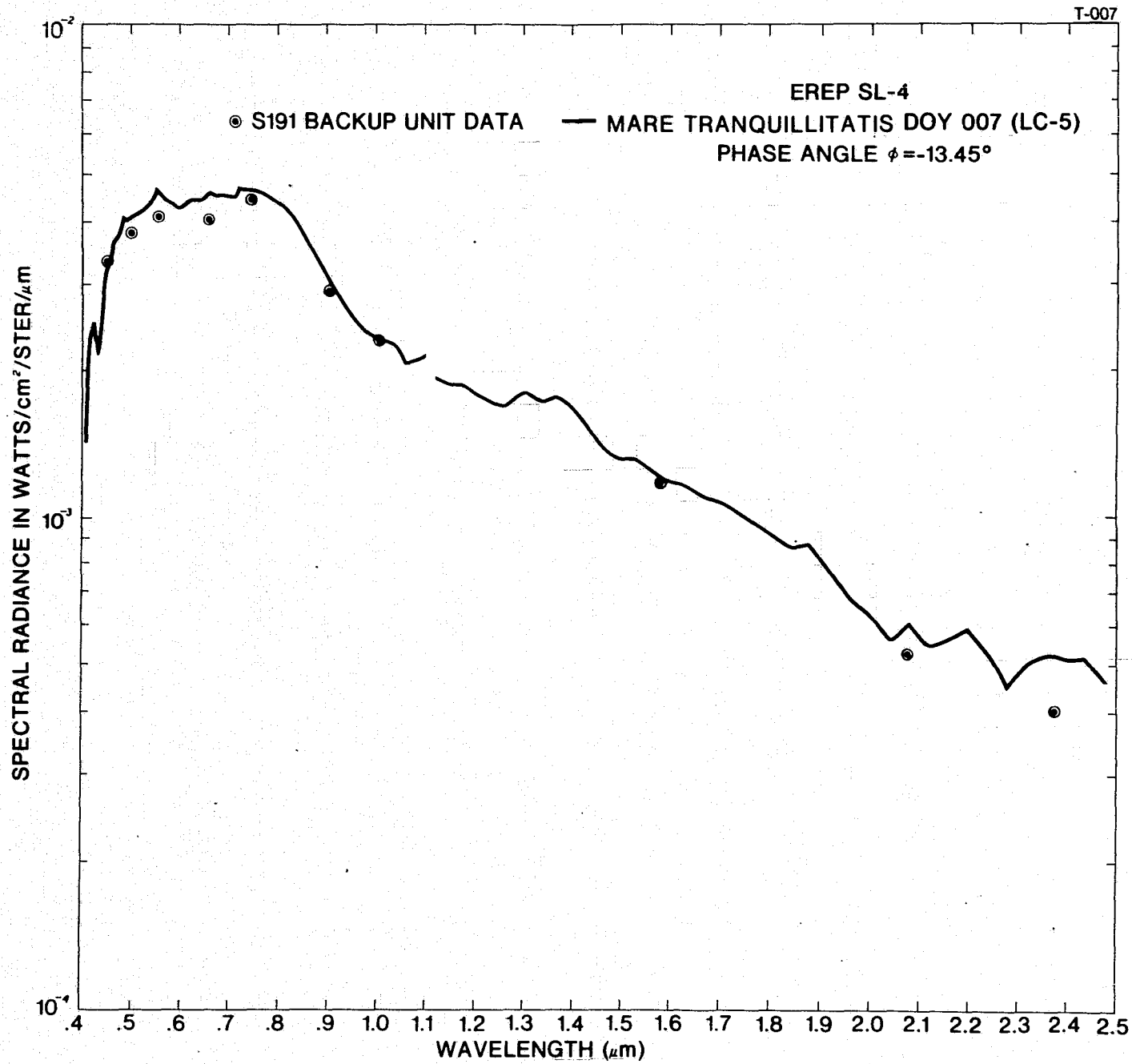



Figure 9.— Mare Tranquillitatis DOY 007 (LC-5).

on (LC-4) DOY 343 (one of the days when a large amount of backup unit data was obtained), plus (LC-3) DOY 254 with differences on the order of 2 percent. Conversely, Mare Tranquillitatis, in the same day, does not fit the backup unit prediction very well and is generally high by a factor of 15 percent. All EREP data falls within about 15 percent of the backup unit's prediction; however, no clear cut phase angle versus radiance function appears to exist for comparing small phase angle changes on different lunations. Other factors that will be described may explain this non-correlation.

## 2.2 INTERCOMPARISON OF S-191 LUNAR DATA

Before the moon was selected as an external calibration source, an extensive literature search was undertaken to determine its suitability. The major problem was in matching the illumination geometry for selected areas. The best solution lay in selecting uniform Mare areas and taking data at approximately the same relative times during different lunations. It was realized that the same precise illumination geometry is never reproduced; however, the phase angle has been shown empirically (ref. 3) to be an accurate monitor of lunar brightness. This is because the moon's equational plane is inclined to the ecliptic* by 1-1/2 degrees causing luminance longitude* and selenographic* longitude to be very nearly the same.

The moon is not Lambertian in character and a non-linear relationship develops between phase angle and brightness at

*See Definition of Terms, pages vi and vii.

phase angles included within ±5 degrees. A nearly linear relationship exists outside these bounds up until the time that shadowing approaches.

The selection of a proper phase angle is also limited by the fact that color differences and polarization begin to occur at large phase angles. For this reason, angles were chosen close to full moon but outside the non-linear portion of the brightness phase angle relationship.

Several other variables which may cause second-order effects were generally ignored in this instrument analysis. These were:

1. Variation in the solar constant
2. Amount of reflected ashen (earth) light impinging on the moon and reflected back to S-191.
3. Luminescence of the lunar surface as caused by UV, X, and corpuscular energy from the Sun.

   Luminescence of the lunar surface caused by UV, X and corpuscular energy from the sun, however, was investigated on a cursory basis by analysis of the geomagnetic planetary index Kp*. This was obtained for the months and days during the lunar cals from the Journal of Geophysical Research. The values for the sum of Kp during lunar cals are shown on the following page.

*See Definition of Terms, page vi.

| | Σ Kp | Magnetic condition | Remarks |
|---|---|---|---|
| June 14, 1973 (DOY 165) LC-1 | 25-1/3 | Disturbed | |
| Sept. 11, 1973 (DOY 254) LC-3 | 19-1/3 | Disturbed | Changing, Sept. 12 was quiet with Σ Kp = 14 |
| Dec. 9, 1973 (DOY 343) LC-4 | 28 | Disturbed | |
| Jan. 7, 1974 (DOY 007) LC-5 | 4-1/3 | Very quiet | |

The interpretation of this tabulation is that LC-1 and LC-4 would have the greatest possibility of containing luminescing radiation in their S-191 measurements. Because of the closeness in the different radiance value measurements and limited number of lunar cal measurements, further interpretation of this effect has not been attempted.

The S-191 radiance from lunar calibrations for LC-1, LC-3, LC-4, and LC-5, whose times are shown in table I, were all corrected for solar irradiance difference and normalized to LC-1 (DOY 165) to determine what changes had occurred during the Skylab missions. The curves for Mare Serenetatis are shown in figure 10 and Mare Tranquillitatis are shown in figure 11. The normalized responsivities used in each radiance calculation are also plotted in figure 12 so that it could be determined approximately how the detectors were behaving.

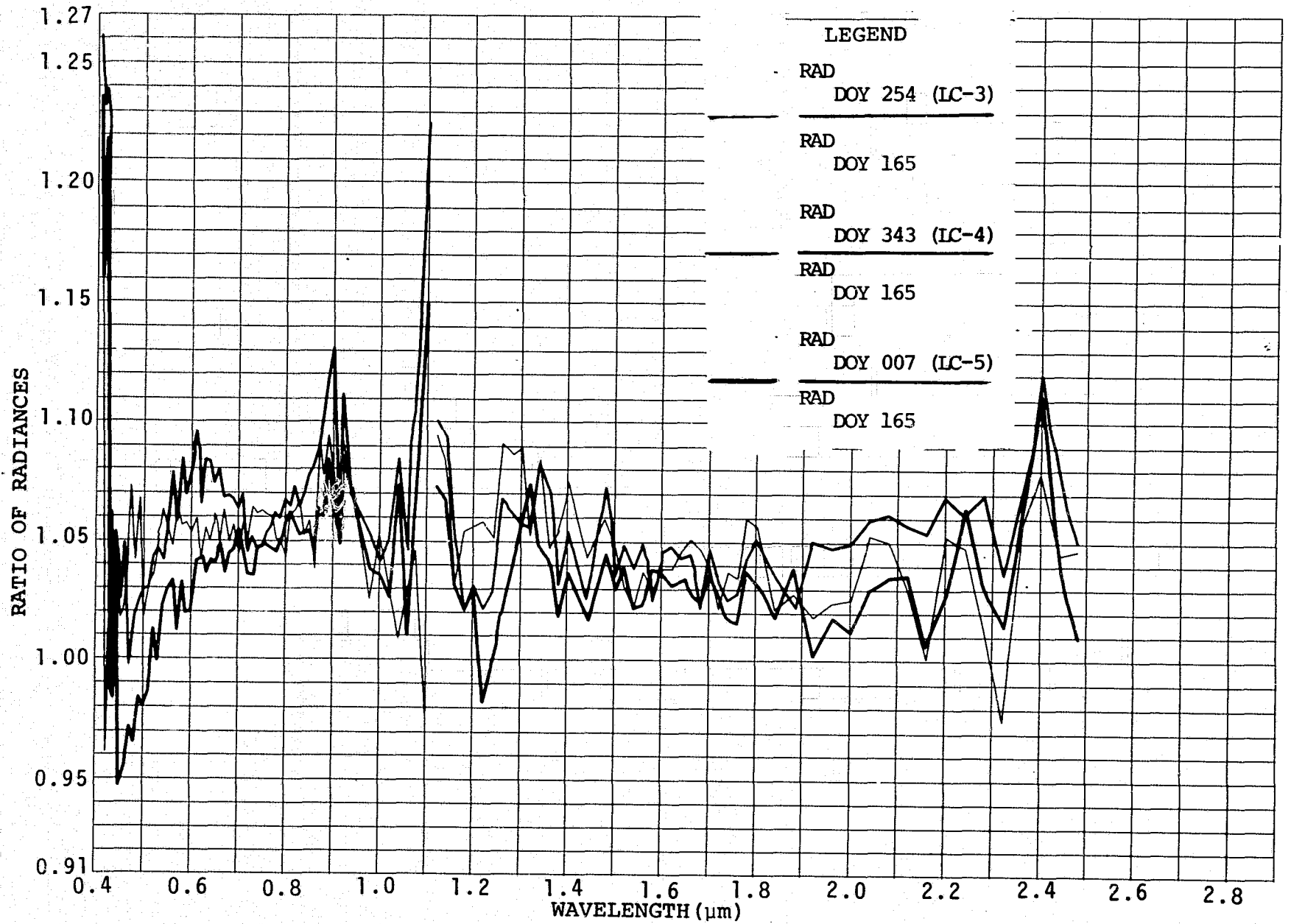



Figure 10. — Relative radiances of Mare Serenetatis to DOY 165 (LC-1).
(Relative solar irradiance correction to DOY 007.)

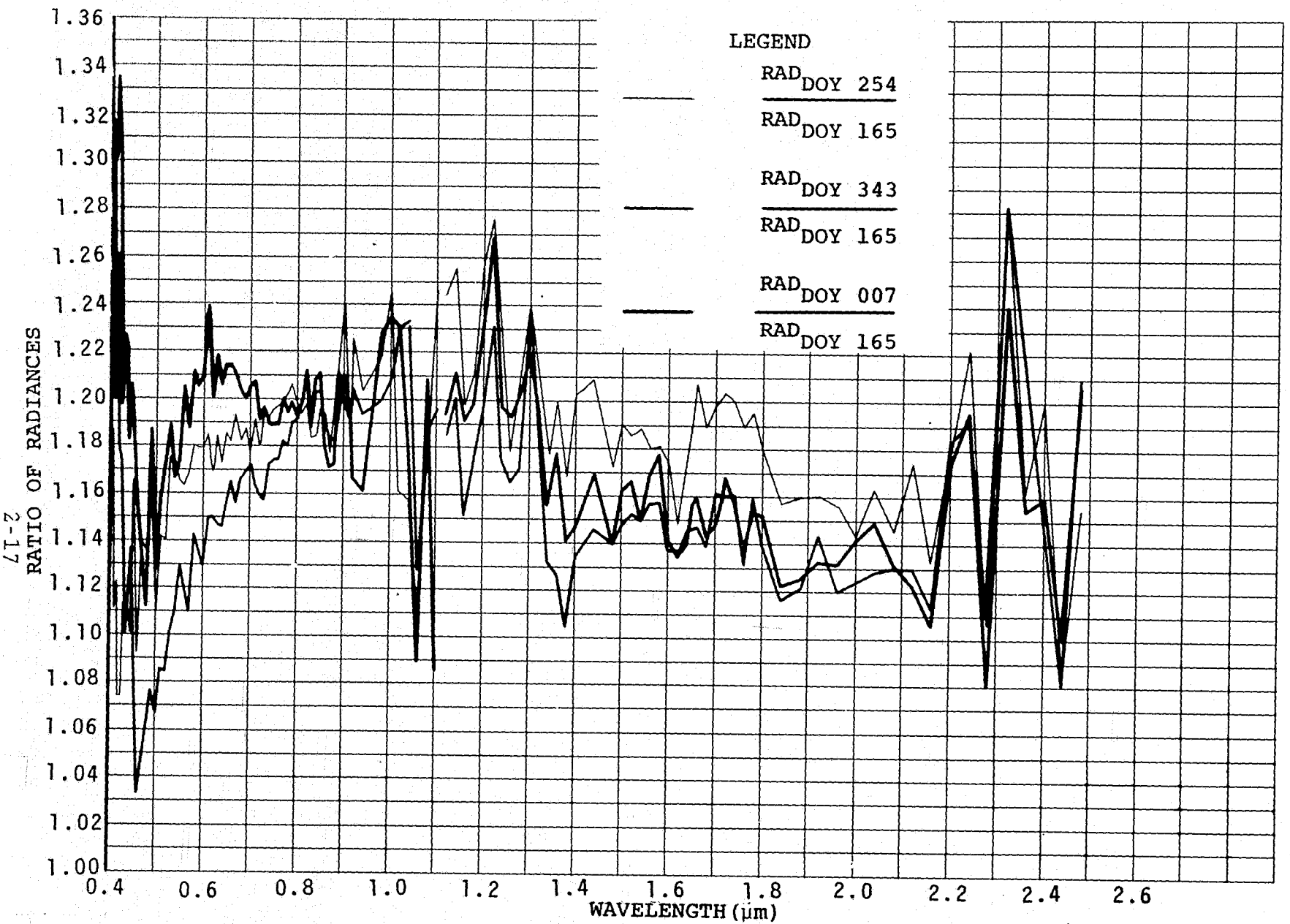



Figure 11. — Relative radiances of Mare Tranquillitatis to DOY 165 (LC-1). (Relative solar irradiance connection to DOY 007)

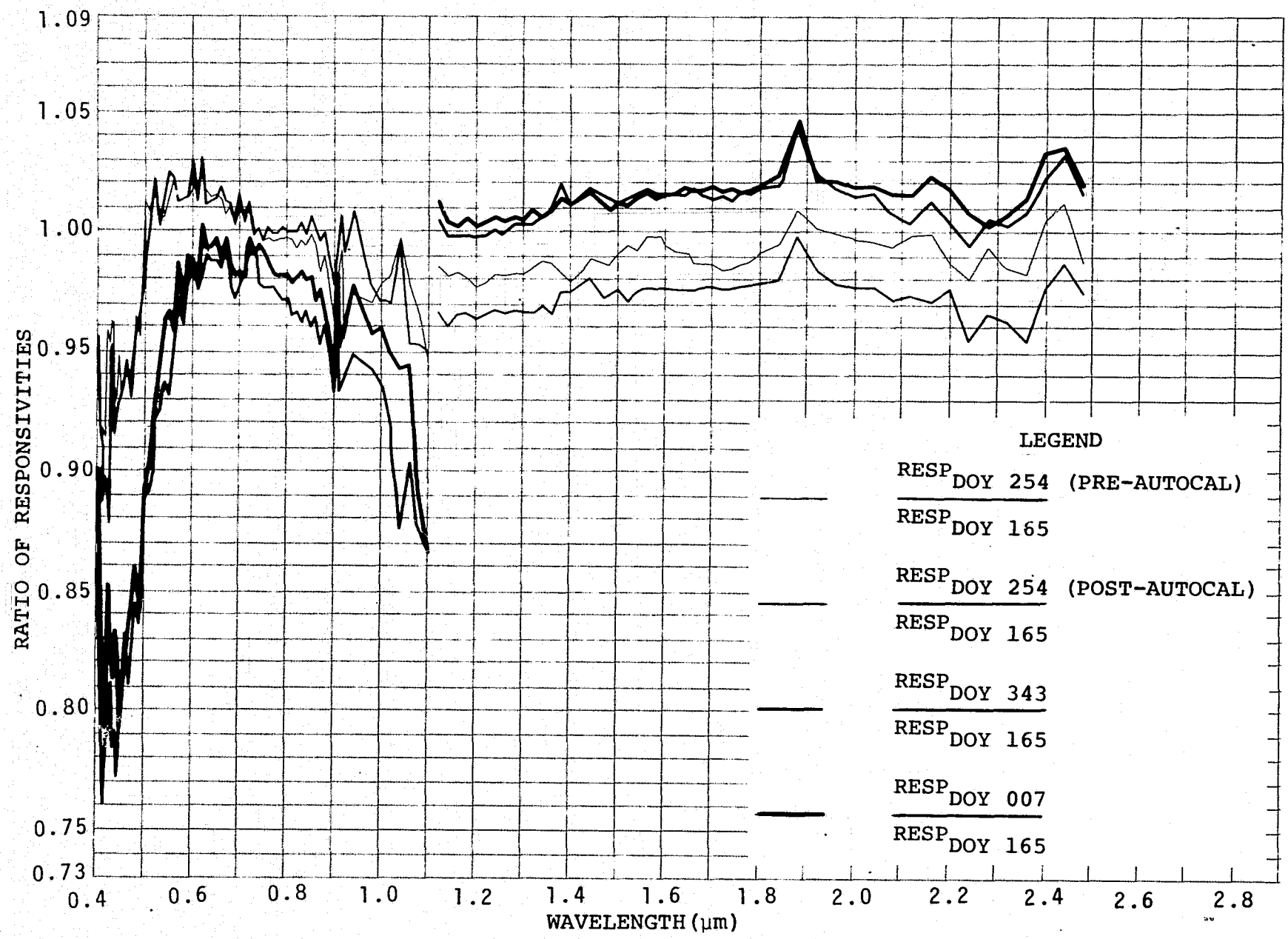



Figure 12. — Relative responsivities normalized to DOY 165 (LC-1).

The interpretation of these curves is rather complex; however, several things become evident. The first is that there is no discernible relationship between phase angle and radiance levels for these small phase angle differences during different lunations. Secondly, Mare Tranquillitatis radiance data from LC-1 does not appear to correlate with the other three lunar calibrations. It would be very easy to say, because of the poor VTS* photography on LC-1, that the instrument was not really pointing at Mare Tranquillitatis during the times identified. However, it is believed that the instrument was pointed properly and that the differences were caused by (1) a relatively poor uniform target and (2) a human-factors problem. The first item is apparent when comparing the three well-identified lunar calibrations in Mare Tranquillitatis to these same calibrations on Mare Serenetatis. There is a great deal more deviation at most wavelengths. The SL-3 astronaut apparently did not cause S-191 to "look" at the same position on Mare Tranquillitatis as did the SL-4 astronaut. This is witnessed by a greater deviation between DOY 254 (LC-3) and DOY's 343 (LC-4) and 007 (LC-5).

The human-factors problem is caused by the fact that the SL-2 astronaut was instructed only to look at large, uniform, dark areas on the moon. The poor LC-1 VTS photography indicated that he was looking at Mare Tranquillitatis. Mare Tranquillitatis subtends approximately 2-1/2 milliradians and it is probable that several 1 milliradian (field of view of S-191) variable radiance areas exist within this total area. With the previously mentioned set of instructions,

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*See Definition of Terms, page vii.

the SL-2 astronaut most probably picked the darkest area within Mare Tranquillitatis. However, when it became known to the SL-3 and SL-4 astronauts that Mare Tranquillitatis was the target, it is suspected that they "centered" on Mare Tranquillitatis, which contains a rather bright protuberance near the center, thus explaining the difference in LC-1. Mare Serenetatis, which only subtends about 1-1/2 milliradians, does not allow for these variations and will be used as the standard in further analysis.

The plot of normalized Mare Serenetatis data should have canceled out most detector anomalies unless they occur between autocal and data take time and show only lunar changes, lamp changes, and optical path (including external mirror) changes.

A general trend can be detected in the normalization. First, the deviation from the mean in the 0.7 through 0.9 μm and 1.5 through 1.75 μm bands is less than about ±1-1/2 percent for LC-3, LC-4, and LC-5. This is very close for over 100 days difference in mission time and indicates, along with the statistical flow of the curves, that lunar spectral radiance differences for slightly different phase angles are not readily detectable from these limited samples.

Several remaining spectral regions in the Mare Serenetatis normalized curve have high deviations. Several instrument anomalies could cause these deviations. Some of the possible ones are as follows:

1. 0.4 to 4.5 μm region – silicon drift at low outputs between autocal and data take and slight lamp drift between autocal to autocal.

2. 1.0 to 1.1 μm region – silicon drift at low outputs between autocal and data take.

3. 0.9 to 1.5 μm region – cal lamp does not repeat peak wavelength output after each turn-on, possibly because of insufficient warmup time.

4. 1.9 to 2.48 μm region – possible thermal effects in cal lamp envelope.

Further work would be needed to determine and sort out the specific causes of these high deviations, if indeed there is enough lunar calibration data for a good statistical evaluation.

## 2.3 COMPARISON OF LUNAR DATA FROM S-191 AND THE LITERATURE

The most appropriate comparison to the literature is with McCord and Johnson's (ref. 4) relative spectral reflectance curve on Mare Serentatis. McCord and Johnson took data from a standard area in Mare Serenetatis (18.7°N, 21.4°E) of approximately 15 km diameter with 52 narrow band interference filters covering the 0.3 to 2.5 μm region. The measurements were made through telescopes at Cerro Tololo Inter-American Observatory and Mt. Wilson Observatory. The relative spectral flux from the lunar area was measured through each of the filters, as well as the flux from standard stars. This data from the standard stars were

used to calibrate the instrument and atmosphere. Several ratios were established to obtain the relative spectral measurements. These were:

$$\rho\left(\begin{array}{c}\text{relative spectral}\\ \text{reflectivity of}\\ \text{Mare Serenetatis}\end{array}\right) = \frac{\begin{array}{c}\text{measured spectral}\\ \text{flux of Mare Serenetatis}\end{array}}{\begin{array}{c}\text{measured spectral}\\ \text{flux of standard stars}\end{array}} \times \frac{\begin{array}{c}\text{tabulated spectral}\\ \text{flux of standard stars}\end{array}}{\begin{array}{c}\text{tabulated spectral}\\ \text{flux of sun}\end{array}}$$

The tabulated flux of the standard stars were obtained from the works of Oke (ref. 5) and Oke and Schild (ref. 6) and tabulated solar fluxes from Labs and Neckel (ref. 7). Some data in these curves was missing due to the lack of information on standard stars in the near infrared.

McCord and Johnson also ratioed the flux from the standard area of Mare Serenetatis to other areas on the moon including an area in Mare Tranquillitatis encompassing the Apollo 11 landing site (Tranquillity Base).

The spectral reflectivity of returned Apollo 11 disturbed surface fines were measured by Adams and Jones (ref. 8). McCord and Johnson, by proper reverse ratioing of Adams and Jones data were able to develop the equivalent spectral measurement for Mare Serenetatis. The comparison to their telescope measurements was excellent if not remarkable, and led them to conclude that the spectral measurement of small samples of distrubed material are indeed representative of the larger undisturbed area telescope measurements. In addition, they concluded that the spectral areas in which they were unable to make measurements (because of unavailability of standard star data) could be described by the

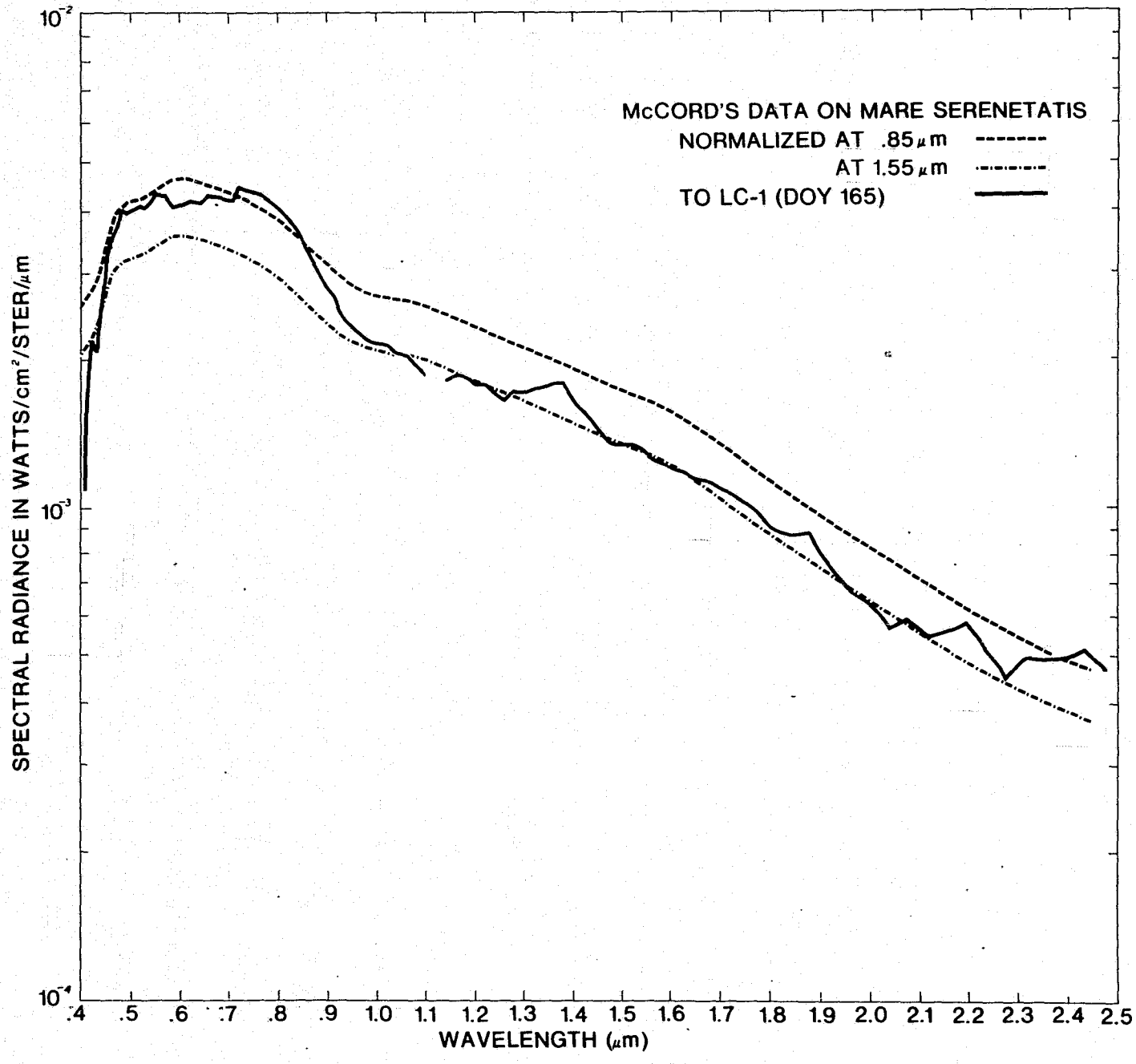



Figure 13. – Comparison of McCord's data and EREP data.

curve derived from the measurements of Adams and Jones (ref. 8). This derived curve for Mare Serenetatis by McCord and Johnson is the basis of comparison to S-191.

The conclusions of McCord and Johnson that large undisturbed lunar areas can be spectrally represented by disturbed lunar soil samples is also supported by independent measurements. O'Leary and Briggs (ref. 9) compared spectrometric measurements of Apollo 11 soil fines to earth-based and lunar-orbiter measurements of Mare Tranquillitatis and found excellent agreement.

In making a relative comparison, the McCord data was changed from relative spectral reflectance to relative spectral radiance by multiplication with tabulated solar spectral irradiance (ref 7). The comparison can then be made directly by normalizing McCord's data at selected S-191 wavelengths.

From figure 2, concerning Mare Serenetatis, it is assumed that 0.85 and 1.55 μm are the most stable wavelengths for S-191. Normalizing McCord's data at these wavelengths and plotting against Mare Serenetatis from LC-1 is shown in figure 13.

There is contradiction in relative radiance in comparing McCord's curve and the S-191 curve on Mare Serenetatis at silicon and lead sulfide (PbS) wavelengths. The silicon appears to jut out of the curve on Mare Serenetatis and does not have the smooth rounding of the McCord data. PbS behaves much like McCord's data at the center wavelengths and deviates considerably at the spectral tail.

If PbS has an accurate relative calibration and McCord's data is an accurate description of 1 milliradian field of view subtended at Mare Serenetatis, then silicon output is approximately 20 percent too high. Conversely, this is also true if silicon is assumed to be more accurate.

Both S-191 data and McCord's data have secondary calibration backing their validity; therefore, we can only say that the differences must be in the areas on which data was taken.

## 2.4 PRELIMINARY OFF-BAND RADIATION CORRECTIONS

A computer program has been written by LEC and run on the Univac 1110 computer for calculation of off-band radiation in the S-191.* The program uses S041-2 raw data tapes to generate radiance data either as described in PHO-TR-524 (ref. 12) or with an off-band correction factor applied. The program will also average data over several spectral scans. (The PHO-TR-524 type radiance data is a simple case where off-band radiation is considered equal to zero.)

The program basically implements the responsivity and radiance iterations as described in MSC-05528, (ref 13, pages 7-5n through 7-5q).

The only difference is that off-band transmission $\tau_{off}(\lambda)$ in equations (10) and (13) is assumed to be constant with wavelength and is taken outside the integral. A series

*User's descriptions have been written. W. V. Argo, Jr. wrote the SWL portion (ref 10) and E. L. Downes the LWL portion (ref 11).

of factors F were used in parameterizing $\tau_{off}(\lambda) = 10^{-4}F$; comparisons were made for DOY 007. The results of these calculations for F = 0.22 and 0.00 are graphically shown in figure 14 relative to McCord's data at 0.855 μm.

The graphical method is rather subjective in this determination of off-band radiation since the two curves do not fit well at the longer silicon responsive wavelengths. A relatively good fit is obtained at 0.45 through 0.5 μm at this F factor, however.

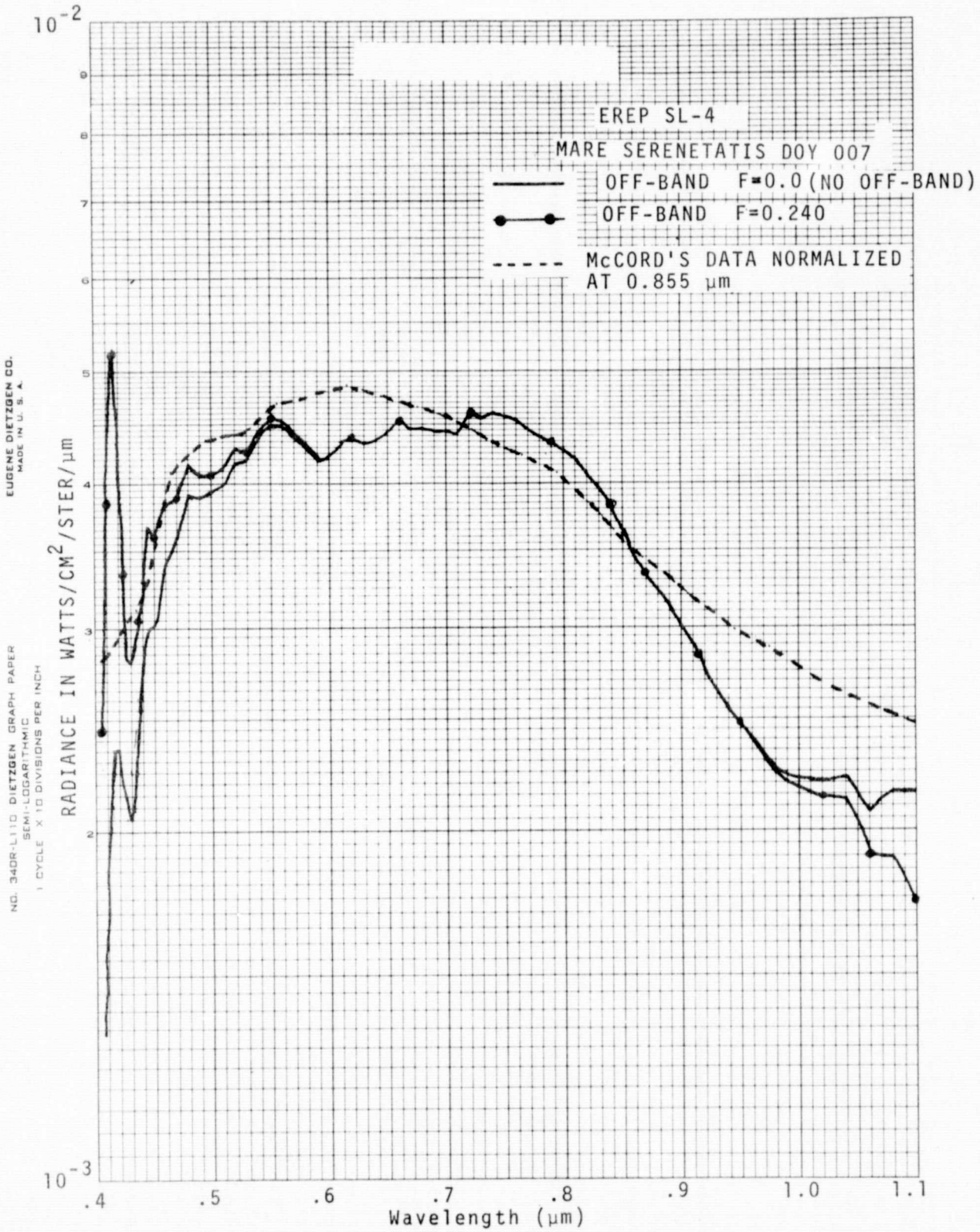



Figure 14. — Off-band correction applied to data from Mare Serenetatis.

## 3.0 LWL ANALYSIS

The LWL analysis consists of intercomparing the radiance values of the 4 lunar calibrations listed in table I and then comparing the most appropriate of those lunar cals to the literature. Additionally, lake/reservoir data measurements by S-191 were compared to apparent radiance predictions from these same lakes/reservoirs by atmospheric programs.

One of the problems experienced with the LWL was the non-colinearity in the responsivity calculations from the heated and ambient autocals. This problem will be discussed before proceeding with the LWL analysis.

### 3.1 AUTOCAL ANALYSIS

Preliminary analysis had been accomplished in MSC-05528 (ref 13, pages 7-5ℓ through 7-5n), which showed that the responsivity required to zero the S-191 aperture radiance when looking at deep space was roughly a function of the reference temperature setting, especially at the lower end of the LWL S-191 spectrum. This gave indications of being an off-band problem.

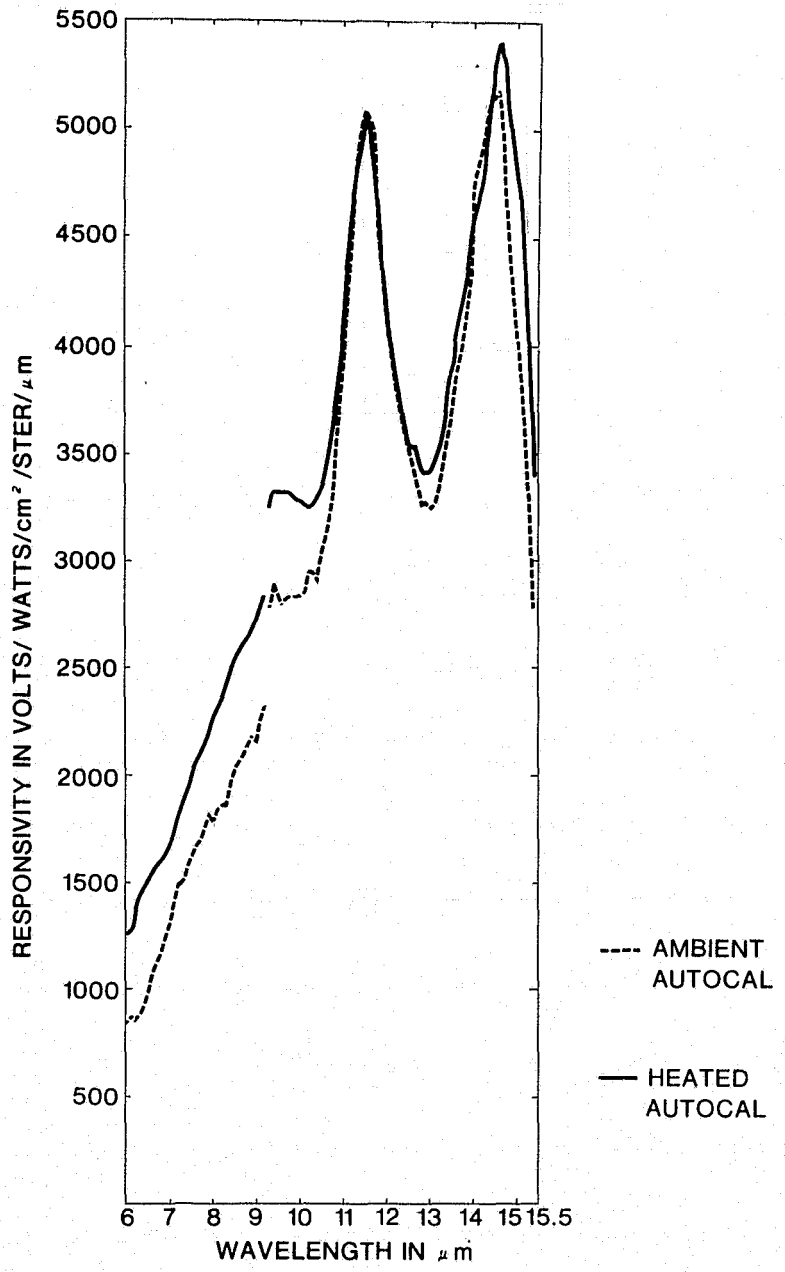
The S-191 program which calculates off-band radiation was used to compute the heated and ambient responsivities to determine if there existed a unique off-band solution at which the responsivities would converge. The results of these calculations were not encouraging because convergence began at assumed spectrally constant values of $\tau_{off}(\lambda)$ but did not approach a unique solution at reasonable values of

$\tau_{off}(\lambda)$, i.e., values from 0.0001 through 0.001 (with the assumption that $\tau_{off}$ is independent of wavelength).

In order to study the problem more closely, the S-191 program was used to compute ambient and heated responsivities for DOY 223 and DOY 254 according to PHO-TR-524 (ref 12, page 4-12). These two days were representative of all reference temperature settings during mission auto calculations except one. These reference temperatures were 8.972°C and -15.242°C. The results of these calculations are plotted in figures 15 and 16. As can be seen, the responsivities are nearly colinear from 10.5 through 14.5 μm but diverge appreciably at the band ends. These center wavelengths responsivities are the most accurate for use in radiance computations.

The cause of this divergence in responsivity is not presently known. Parametric evaluations of errors in system physical constants and off-band calculations have not yielded acceptable solutions. In addition, the responsivities at -15.242°C reference setting are more nearly convergent than those at 8.972°C, which would seem to rule out any kind of background noise limitation. If the heated cals were not being monitored correctly, then the question arises as to why some spectral responsivities are colinear while others are not.

More specific answers would require considerably more responsivity data reduction with the S-191 program which has only recently come on-line. However, the termination of the sensor performance evaluation leaves these questions unanswered, and the final analysis will be evaluated on the basis of available time and data.



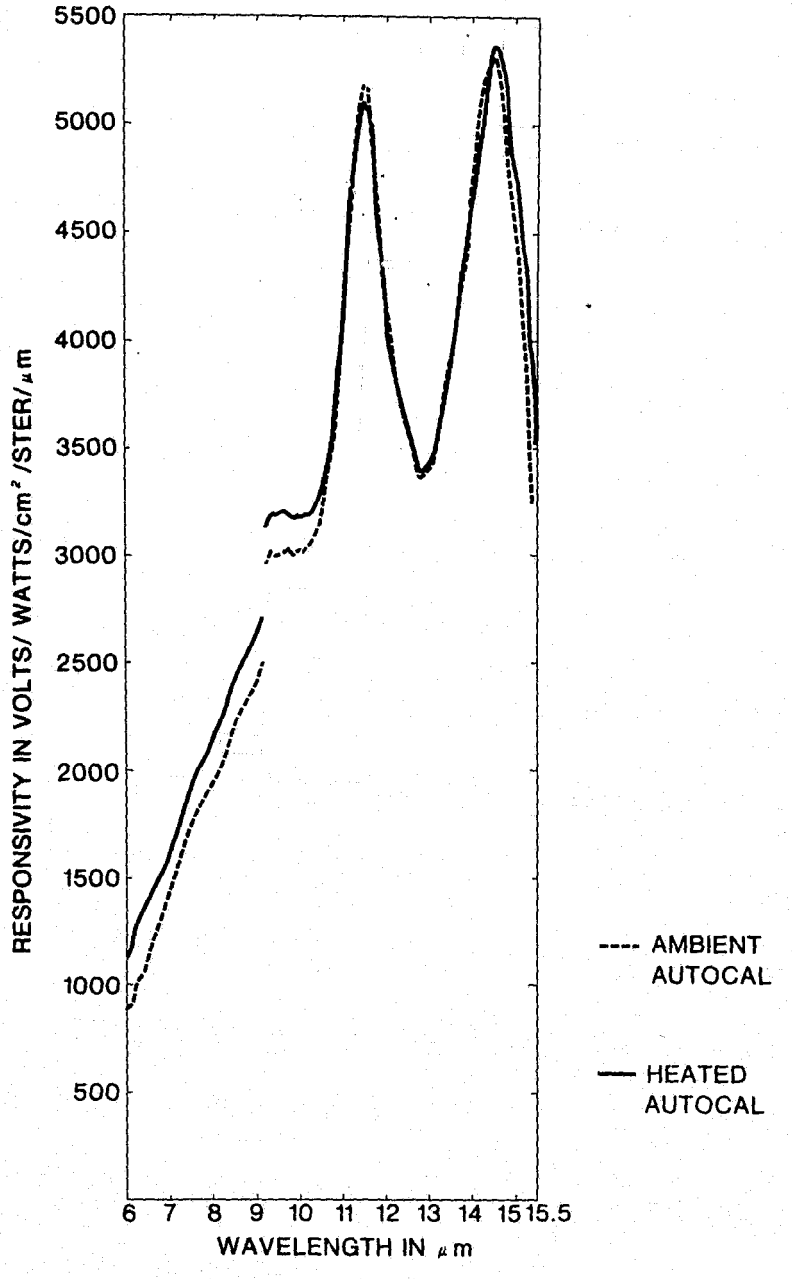

AMBIENT AUTOCAL HOUSEKEEPING DATA

| Time (GMT) | | Htd(°C) | Amb(°C) | Dic(°C) | Ref(°C) | Det(°K) |
|---|---|---|---|---|---|---|
| Start | Stop | | | | | |
| 223:15:30:31.99 | 223:15:30:38.501 | 18.789 | 18.463 | 23.378 | 8.972 | 85.704 |

HEATED AUTOCAL HOUSEKEEPING DATA

| Time (GMT) | | Htd(°C) | Amb(°C) | Dic(°C) | Ref(°C) | Det(°K) |
|---|---|---|---|---|---|---|
| Start | Stop | | | | | |
| 223:15:31:40.064 | 223:15:31:46.613 | 49.099 | 18.165 | 23.462 | 8.972 | 85.495 |

Figure 15. — Responsivities for a 8.972° C reference source temperature.




AMBIENT AUTOCAL HOUSEKEEPING DATA

| Time (GMT) | | Htc(°C) | Amb(°C) | Dic(°C) | Ref(°C) | Det(°K) |
|---|---|---|---|---|---|---|
| Start | Stop | | | | | |
| 254:14:00:00.583 | 254:14:00:07.085 | 50.546 | 23.221 | 24.781 | -15.242 | 86.260 |

HEATED AUTOCAL HOUSEKEEPING DATA

| Time (GMT) | | Htd(°C) | Amb(°C) | Dic(°C) | Ref(°C) | Det(°K) |
|---|---|---|---|---|---|---|
| Start | Stop | | | | | |
| 254:14:00:40.533 | 254:14:00:47.036 | 49.044 | 23.298 | 24.866 | -15.242 | 86.191 |

Figure 16. – Responsivities for a -15.242° C reference source.

## 3.2 INTERCOMPARISON OF LWL MARE DATA

The same time periods intercompared in the SWL were also compared in the LWL. The data on the moon have all been calculated using the heated autocal responsivities because these temperatures are closer to that of the moon than the ambient temperatures.

The radiance data collected on Mare Serenetatis is shown in figure 17 and Mare Tranquillitatis in figure 18. Again, it can be noted that Mare Serenetatis is a much better behaved target than is Mare Tranquillitatis. LC-5 has a serious anomaly between 8.2 and 10 μm and is low by about 10-15 percent at 9.5 μm. This correlates to the SWL data on LC-5 as a drop in relative radiance from .4 to .55 μm can be noted in figure 10 on Mare Serenetatis.

The exact extent of this anomaly can be studied more closely in figures 19 and 20 which are normalized radiances of Mare Serenetatis and Mare Tranquillitatis to data on DOY 165 (LC-1).

Low data in the LWL suggests 4 possible problems; (1) the instrument was not pointing properly, (2) internal changes occurred in the instrument, (3) the lunar target changed, or (4) the external mirror or the vicinity around S-191 became degraded or contaminated.

Mare Tranquillitatis (DOY 007) in figure 20 also shows this anomaly which eliminates the possibility that the instrument was not pointed properly. In order to prove that instrument internal values had not changed, a normalization

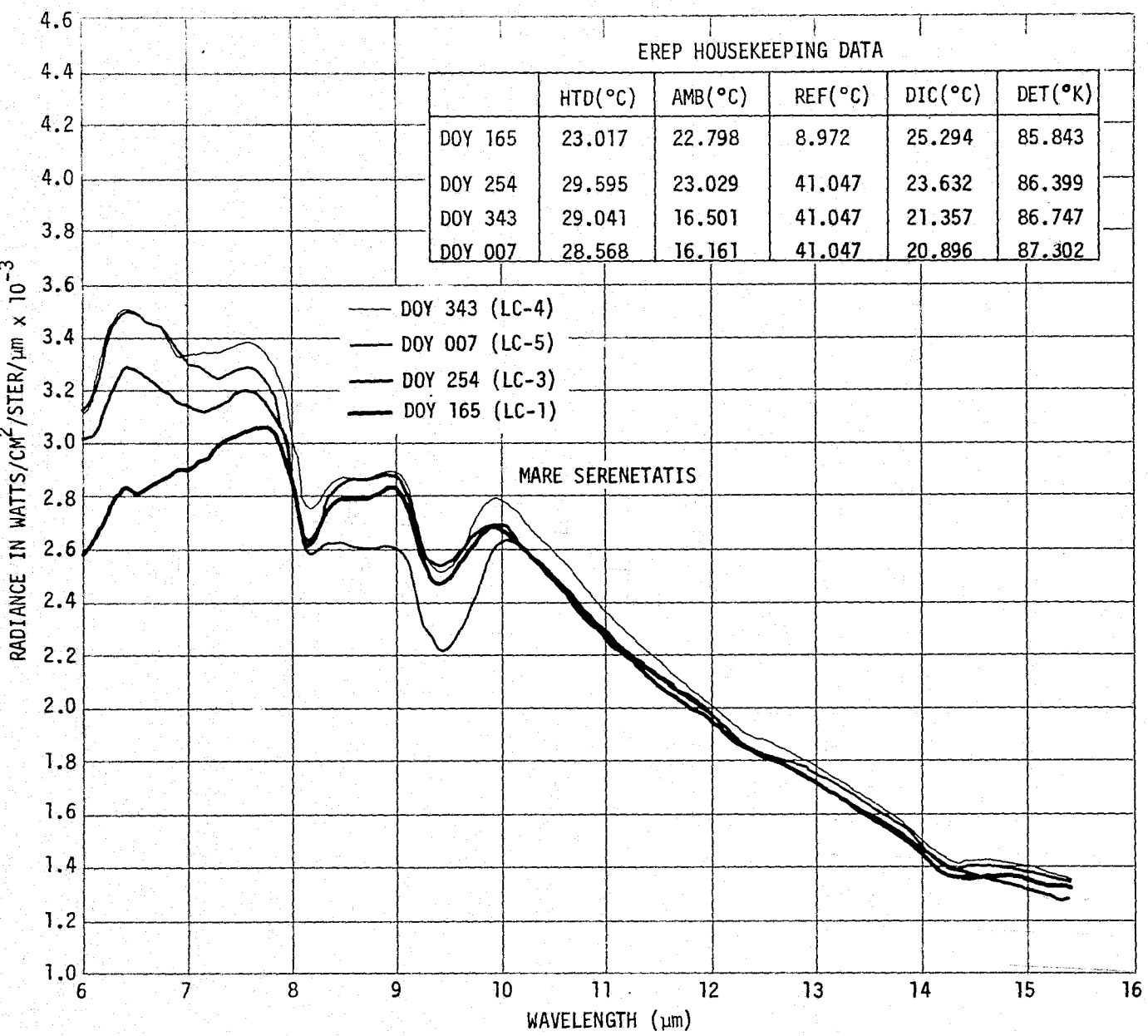



Figure 17. — LWL radiance data from Mare Serenetatis.

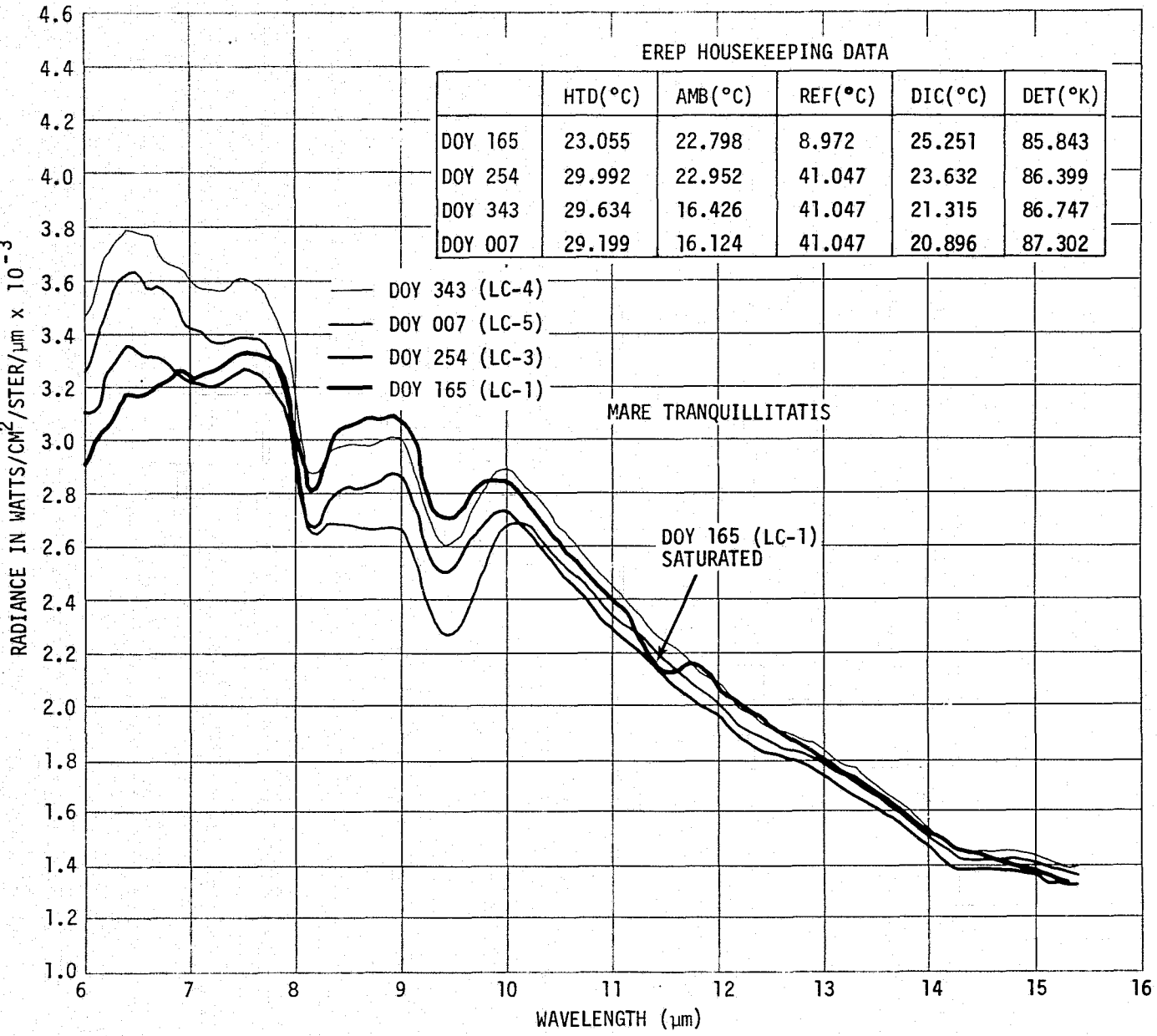



Figure 18. — LWL radiance data from Mare Tranquillitatis.

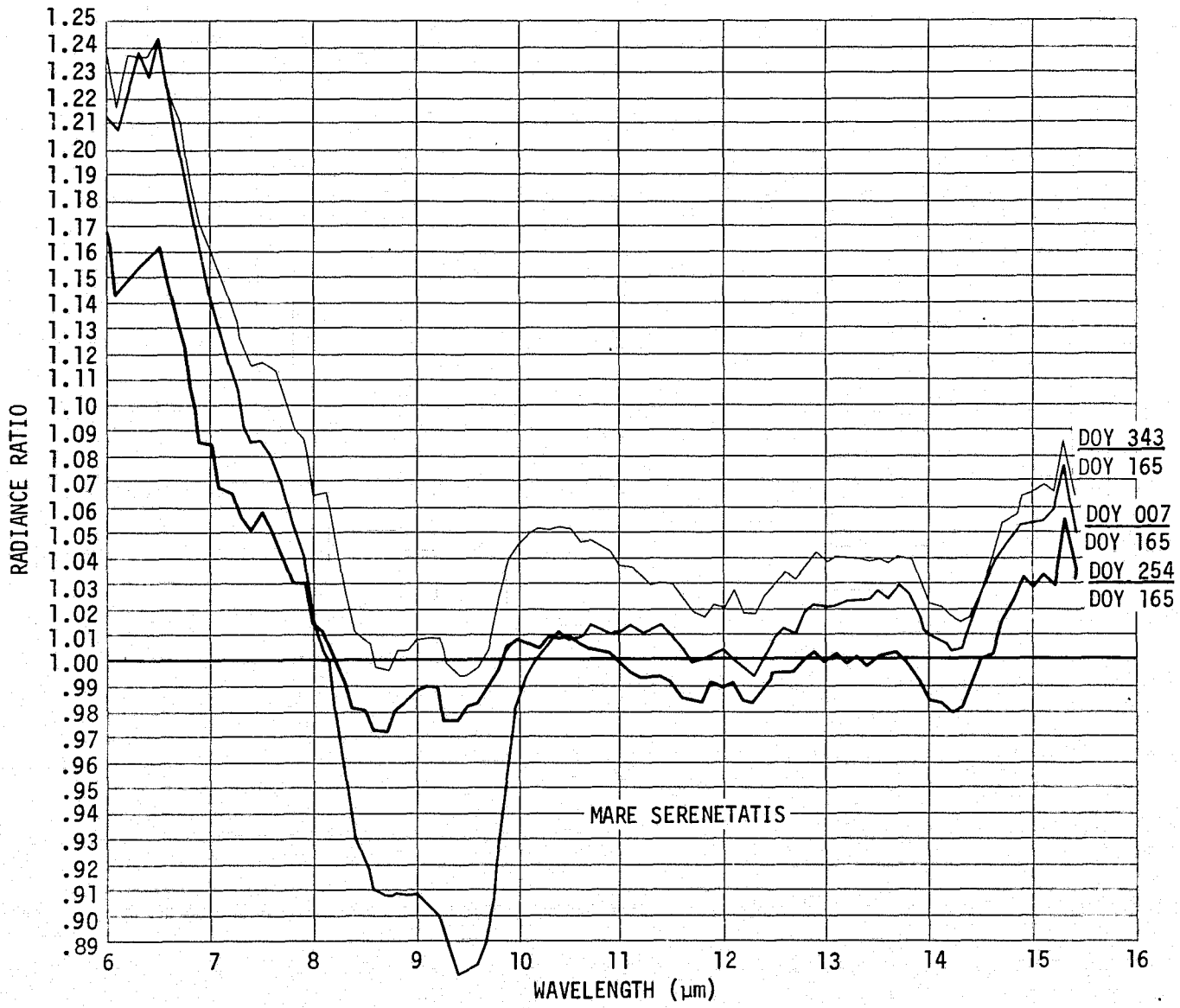



Figure 19. – Radiance ratio from Mare Serenetatis relative to DOY 165 (LC-1).

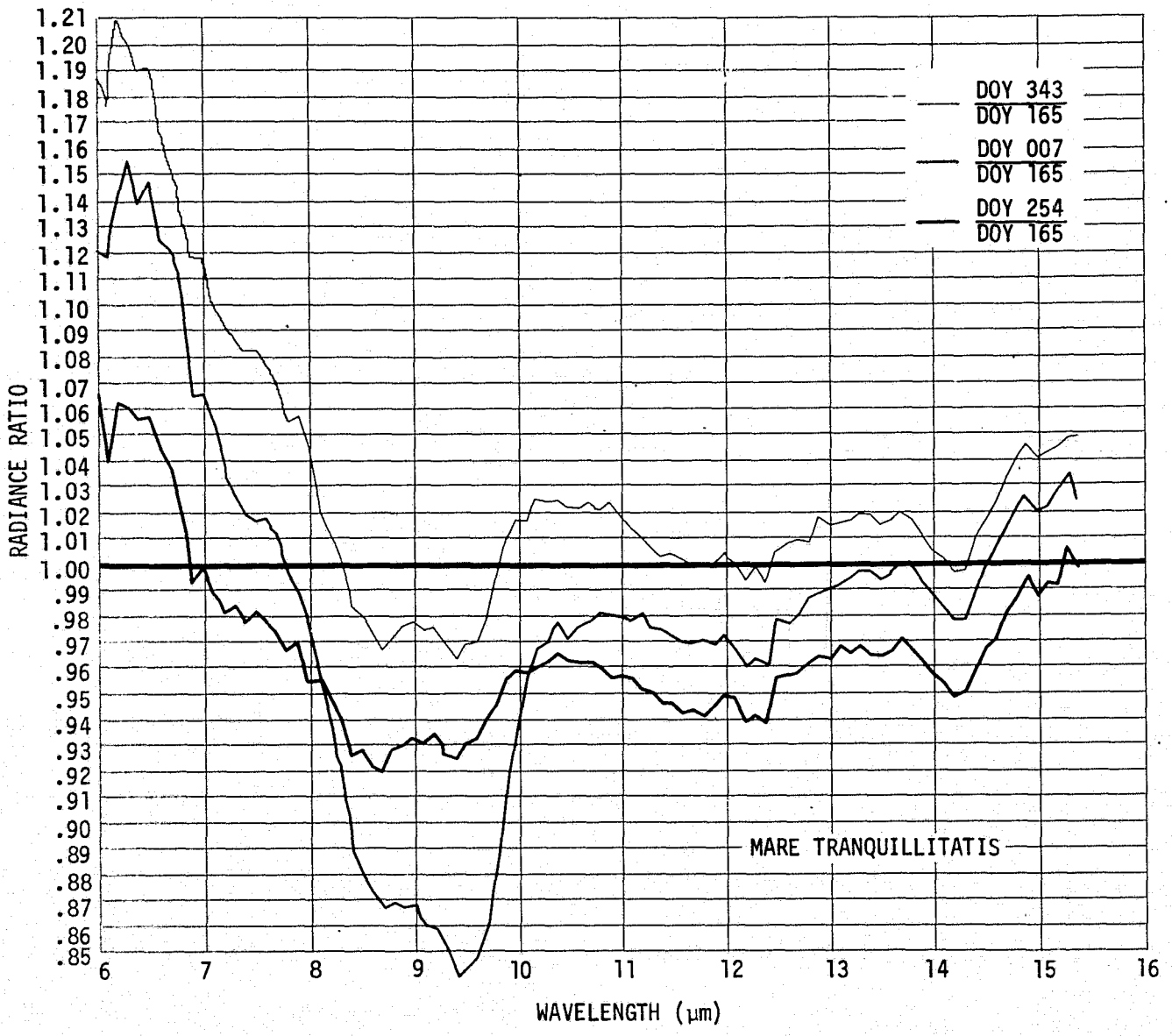
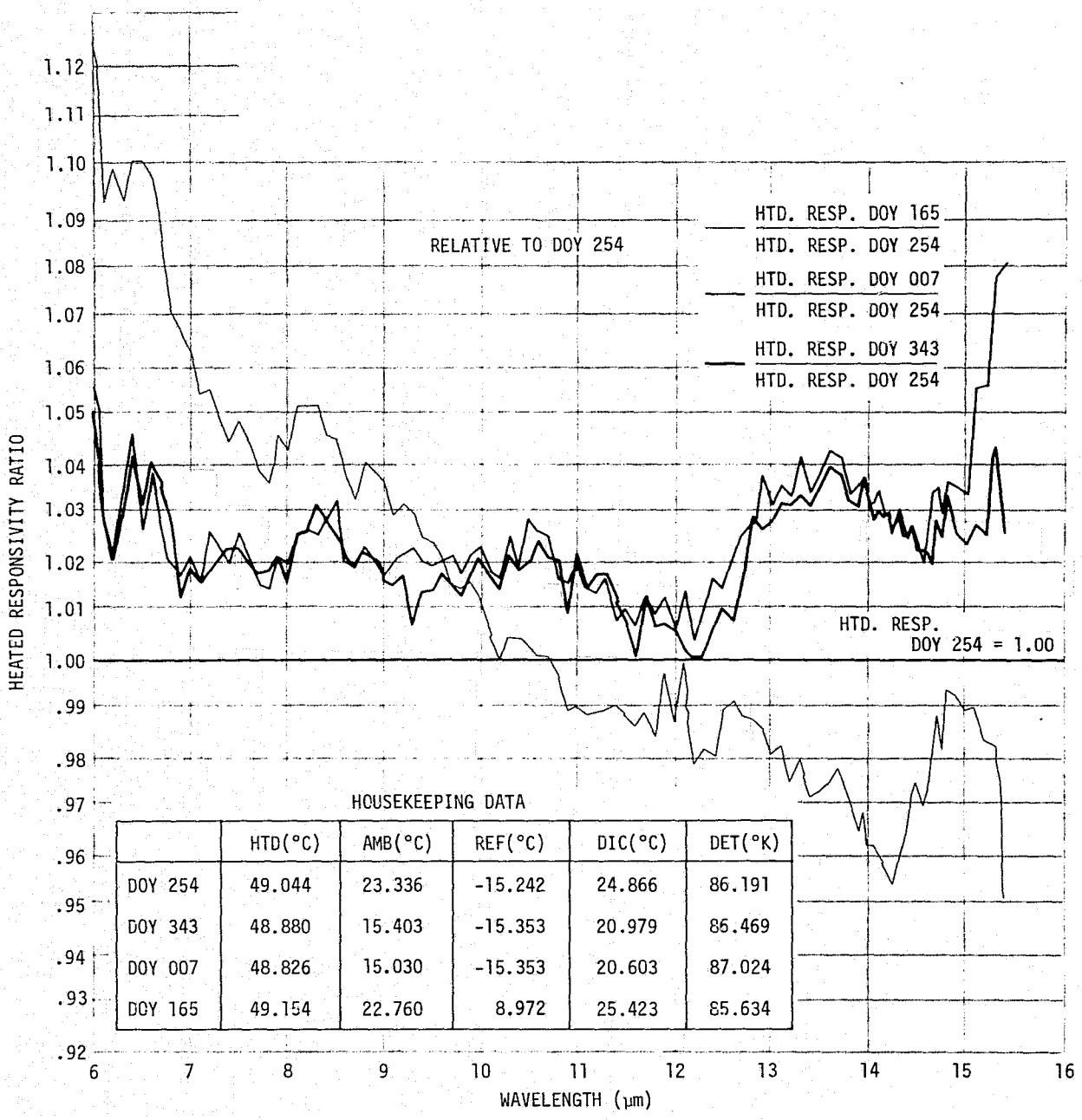



Figure 20. — Radiance ratio from Mare Tranquillitatis relative to DOY 165 (LC-1).

was made on heated responsivities used in LC-1, LC-4, and LC-5 to the heated responsivity calculated for DOY 254 (LC-3). The results are shown in figure 21. No appreciable internal changes occurred in S-191 on DOY 007. The possibility that the spectral exitance of the Mares changed appreciably between LC-1, LC-3, LC-4, and LC-5 is not a likely occurrence.

Therefore, it is assumed that some sort of contamination/degradation occurred in the external mirrors or in the near vicinity of Skylab. This is supported by the SWL analysis as serious degradation occurred in the 0.45 to 0.55 μm region on Mare Serenetatis data on DOY 007.

The data in figure 19 on Mare Serenetatis appears to "tail up" at the spectral ends relative to DOY 165. One of the reasons attributed to this is that DOY 165 is the only lunar cal in which the reference source setting was constant during the auto cal and the data take. Because of slight saturation at a few wavelengths during this first lunar cal, the flight plan was changed for the follow-on lunar cals so that the reference source was changed after the auto cal from -15.242°C to 41.047°C before lunar data takes. This was great for non-saturation, but poor for calibration. Because the reference source setting was not changed on LC-1, it is considered to be the most accurate description of LWL relative radiance of Mare Serenetatis. A plot of Mare Serenetatis in figure 22 on DOY 165 versus the radiance of a 370°K and 380°K blackbody shows very good agreement except at apparent absorption bands centered at 8.2 and 9.4 μm.




HOUSEKEEPING DATA

| | HTD(°C) | AMB(°C) | REF(°C) | DIC(°C) | DET(°K) |
|---|---|---|---|---|---|
| DOY 254 | 49.044 | 23.336 | -15.242 | 24.866 | 86.191 |
| DOY 343 | 48.880 | 15.403 | -15.353 | 20.979 | 86.469 |
| DOY 007 | 48.826 | 15.030 | -15.353 | 20.603 | 87.024 |
| DOY 165 | 49.154 | 22.760 | 8.972 | 25.423 | 85.634 |

Figure 21. — Heated responsivity ratios used in lunar cal data.

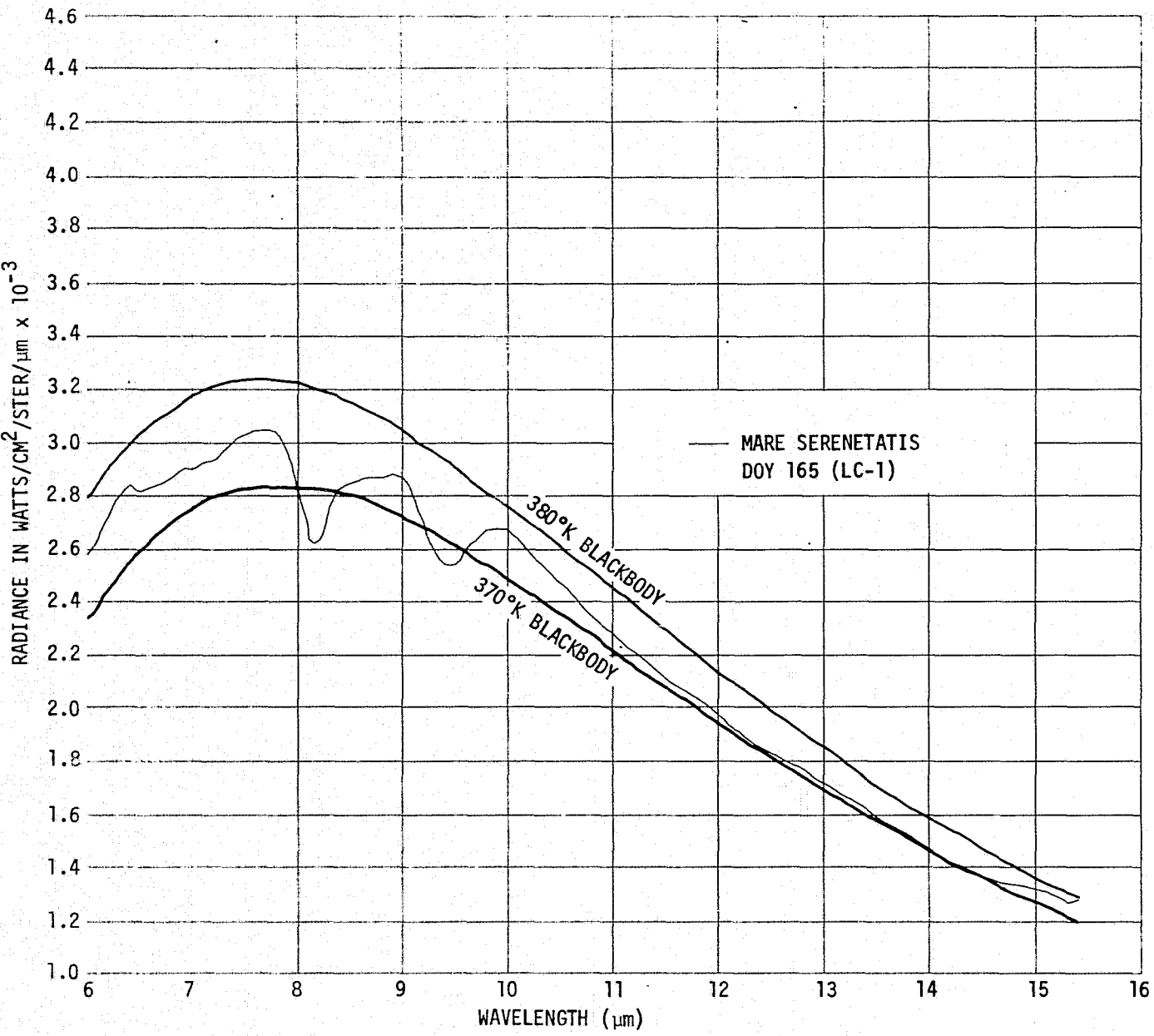



Figure 22. — Comparison of Mare Serenetatis radiance from LC-1 and equivalent blackbody radiance.

Mare Tranquillitatis, in figure 18, shows the same low readings from 8.2 through 10 μm on DOY 007 as does Mare Serenetatis. In addition, a much greater spread of radiances is encountered from one location to the next. This is attributed to Mare Tranquillitatis being a much larger and less uniform target than Mare Serenetatis. In addition, Mare Tranquillitatis is closer to the lunar equator and may be affected by solar specular radiation. This may explain the higher readings on DOY 343 (a partial lunar eclipse occurred on DOY 344). On LC-1 (DOY 165), the reading is high compared to Mare Serenetatis; it was speculated in the SWL analysis that this was caused by looking at a dark area within Mare Tranquillitatis. This is confirmed by the LWL measurement. There was also saturation of LC-1 at wavelengths between 11.1 through 11.9 μm. A change or reduction in the peak between the two absorption bands at 8.2 and 9.4 μm is also noted on DOY 254.

## 3.3 COMPARISON OF EREP LUNAR DATA TO THE LITERATURE

A comparison can be made to the literature because Shorthill (ref 14) performed visible and thermal scanning of the moon in 1963 and 1964. A very small field-of-view optical scanner was used and the output in the thermal band was plotted into a thermal contour map of the moon for different Mare analyses. Shorthill's instrument used a large bandpass, as compared to S-191, and collected energy from about 9.6 through 12.2 μm.

An accurate comparison would require convolution of the energy under the S-191 spectral radiance curve from 9.6 through 12.2 μm and comparison to Shorthill's measured area

(1 milliradian S-191 coverage) averaged temperature values. Because of the time limitation for completing this report, the overall system spectral response curve is considered flat over the bandpass of Shorthill's instrument (ref 14, page 9) which is a close approximation.

A plot of Shorthill's area averaged Mare thermal data versus phase angle gave what appeared to be some physical discrepancy or error in the data. However, from measurements by EREP over different lunations, this discrepancy also appears. Taking phase angle alone as a measure of physical quantities on the moon from one lunation to the next is not a complete description of the optical properties of the moon. For this reason, a more complete match in the infrared would be at the same solar distance and illumination angles. Shorthill took thermal data on the moon in December of 1964 prior to a total eclipse of the moon (ref 14, page 85). EREP also took data in December 1973 before a partial eclipse of the moon. A calculation was made on this data and the comparison as follows:

| | Mare Serenetatis 27°N; 18°E* | | Mare Tranquillitatis 7°N; 30°E* | |
|---|---|---|---|---|
| Shorthill's data 12/17/1964 20H 16.2M UT | $\theta$ 27.26° | $\phi$ 172.49° | $\theta$ 16.94° | $\phi$ 114.02° |
| EREP data 12/09/1973 00H 25M UT | 28.19° | 164.853° | 20.41° | 110.34° |

Where $\theta$ is the solar illumination angle from zenith and $\phi$ is the azimuth of the sun direction from the north

*Approximate selenographic coordinates at center of Mare.

meridian that passes through the Mare ($\phi$ is + clockwise, - counterclockwise). As can be seen the solar illumination angles are closely matched on Mare Serenetatis and slightly under 4° difference on Mare Tranquillitatis. The earth direction is close also as the phase angles are -14.77° for EREP DOY 343 (LC-4) and -17° 52' for Shorthill's measurements. Solar irradiation is very nearly the same (both data takes were in December) assuming the solar constant has not varied during 9 years.

The results of this comparison are shown in figures 23 and 24. Radiance values measured by S-191 are 10 to 15 percent lower than Shorthill's measurements and are about 10 percent below his error bounds.

## 3.4 COMPARISON OF EREP S-191 DATA TO ATMOSPHERIC MODEL DATA

The last part of the LWL analysis involves comparing the radiance predicted by atmospheric programs coming from lakes/reservoirs to that measured by the S-191.

The atmospheric program at JSC (ref 15) was basically developed by Dr. Calfee of NOAA with Dr. David Pitts of JSC adding selected features. The program assumes up to 30 homogeneous layers* of atmosphere with each having a constant pressure and constant temperature. The program develops line-by-line data for about 15,250 lines of carbon dioxide, water, methane, ozone, and nitrous oxide into spectral emission and transmission data for each layer. Each of the layers are

*Only 10 were used in our analysis.

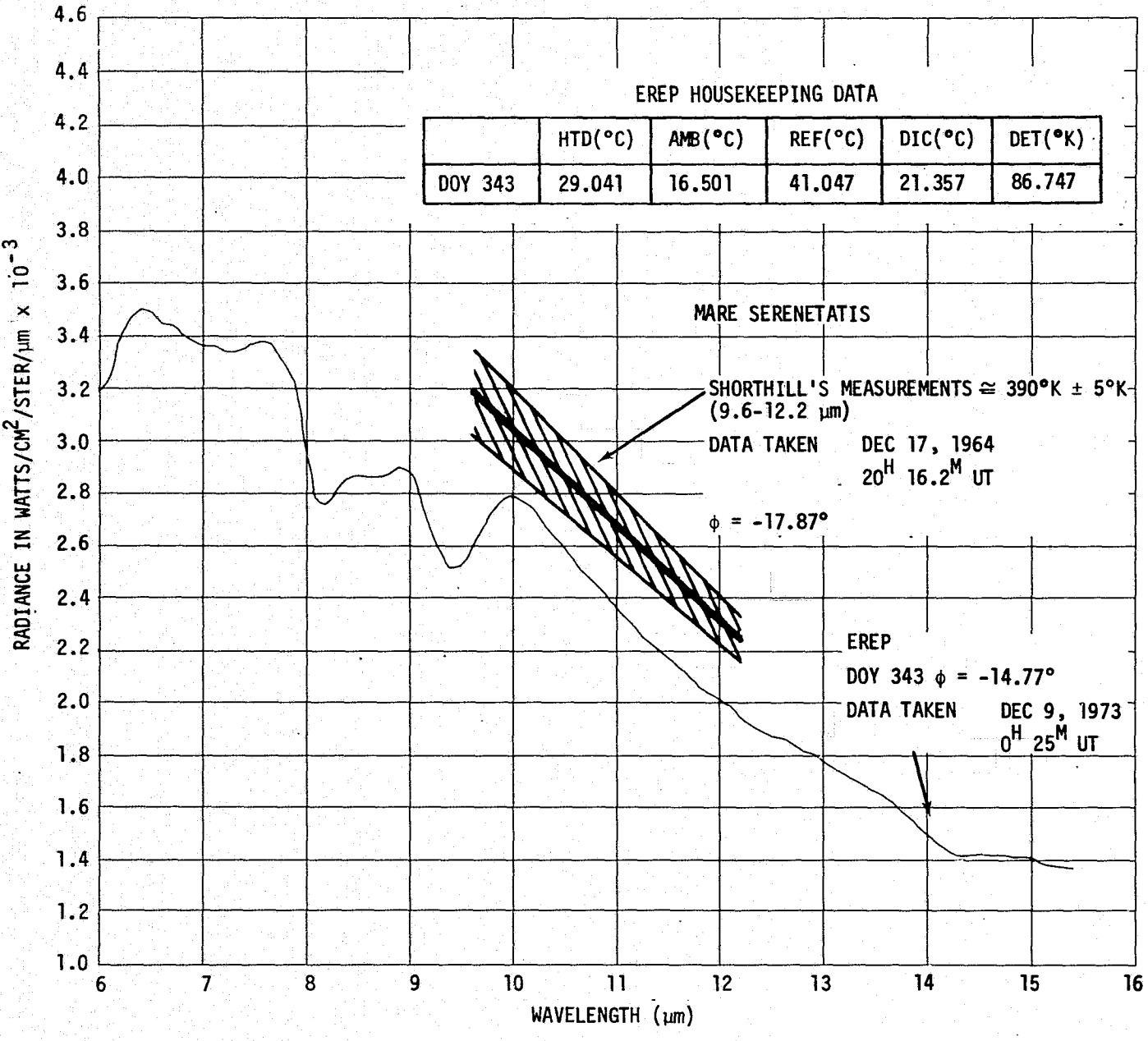



Figure 23. — Comparison of radiance data from Mare Serenetatis (SL-4) by S-191 and Shorthill (ref 6, page 85).

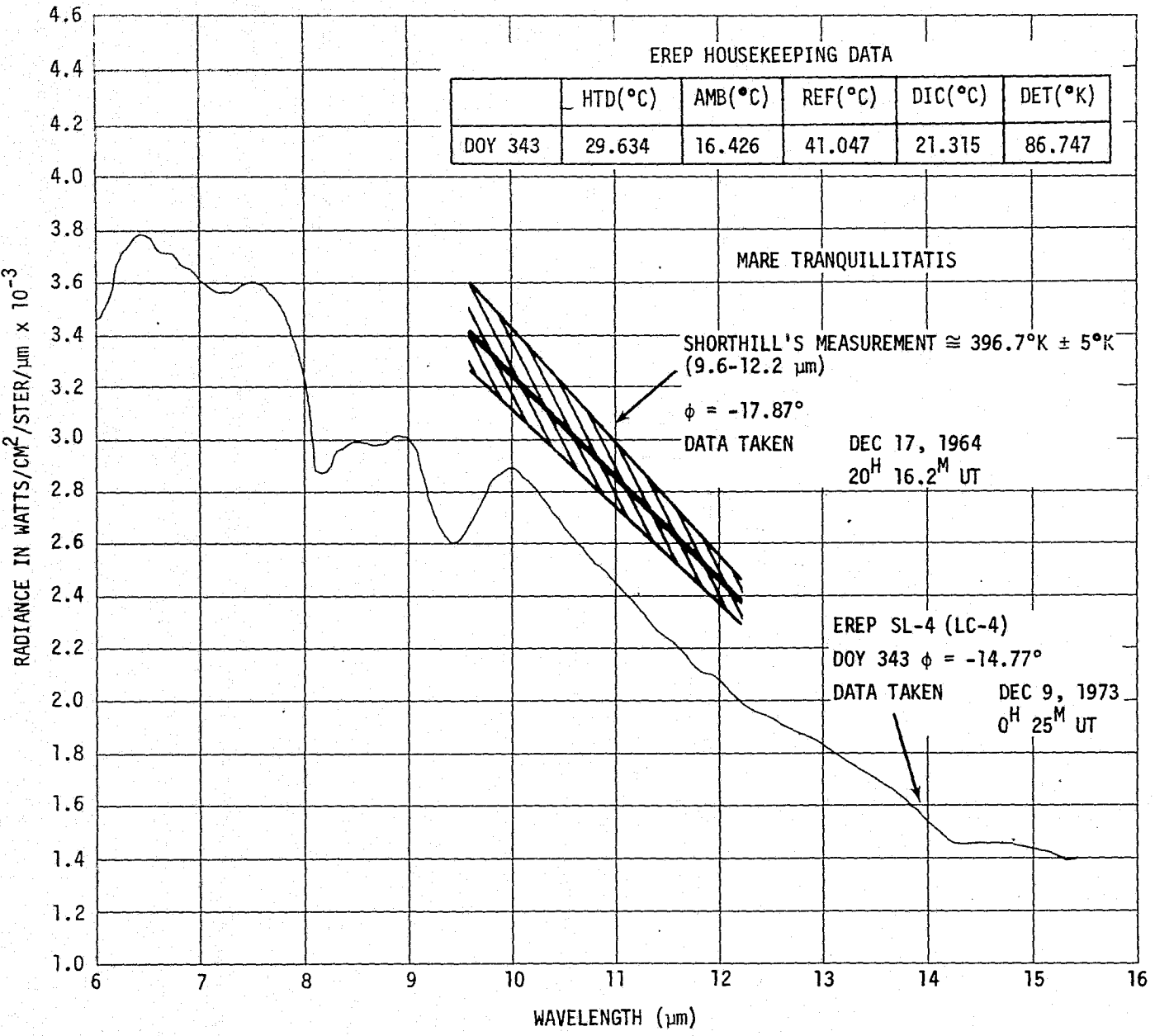





Figure 24. – Comparison of radiance data from Mare Tranquillitatis (SL-4) by S-191 and Shorthill (ref 6, page 85).

then applied to water surface radiance data to develop apparent radiance as viewed from space. This apparent radiance data can then be compared directly to the measurements of S-191.

The Calfee-Pitts atmospheric program requires, as input, the water surface temperature and radiosonde data including altitude, temperature, pressure and dewpoint-depression.

Early in the plan for Sensor Performance Evaluation, it was decided that lake/reservoir sites of opportunity would be chosen rather than planned, pre-instrumented sites. Under these conditions, lake surface temperatures would probably be accurate for relatively long periods between lake temperature measurements and S-191 overflights while radiosonde data would not necessarily remain stable unless weather conditions remained constant. With these limitations in mind, a selection of best lake/reservoir data was made. Table II contains these selections.

The surface temperature for Monroe Reservoir was made on the day of the S-191 flight by a Purdue University Principal Investigation team. Their report indicated that the reservoir was a very constant 25° C except in the shallows along the sides.

Radiosonde data was not available from Monroe Reservoir. However, radiosonde data was available from three stations which lay about 200 miles from each other in a triangle around Monroe Reservoir. These are Peoria, Illinois, Salem, Illinois, and Dayton, Ohio. The radiosonde data from these three stations were collected from the National Weather Service on the day of the S-191 overflight and were taken

TABLE II. – TIME FRAMES FOR
RESERVOIR/LAKE DATA

| LOCATION/MISSION | TAPE START (GMT)<br>[VTS time] – gimbal angles | TAPE STOP (GMT)<br>[VTS time] – gimbal angles |
|---|---|---|
| Monroe Reservoir/SL-2 | 161:14:26:2.20<br>[25:57] – 05 UP, 03 LEFT | 161:14:26:08.815<br>[26:10] – 05 DN, 03 LEFT |
| Lake Titicaca/SL-4 | 027:19:17:56.58<br>[17:56] – 07 UP, 16 RT | 027:19:18:03.04<br>[18:04] – 00 UP, 16 RT |
| Great Salt Lake/SL-4 | 029:17:32:34.74<br>[32:33] – 08 UP, 06 LEFT | 029:17:32:41.23<br>[32:42] – 00 UP, 06 LEFT |

at 161:12:00:00. All data were plotted and showed minor differences, indicating that a front had probably cleared the area. The Salem, Illinois data was finally selected as the radiosonde data to be input into the Calfee-Pitts program.

The temperature of the Great Salt Lake was monitored by a Martin-Marietta team (ref 16, page 11) and was reported to be between 4.5° and 6°C at approximately 41° 15' 00" N longitude and 112° 45' 00" W longitude. This was a position the S-191 was looking at during the S-191 overflight times described in table II. Radiosonde data was also available through the National Weather Service at 029:12:00:00 and was taken at the International Airport in Salt Lake City, Utah.

The last lake data was from Lake Titicaca. This data is important because Lake Titicaca is at 12,520 feet and is above most of the atmosphere. The comparison of S-191 to the lake temperature would exclude an atmospheric program.

A comparison was also desired of S-191 output to Lake Titicaca with an atmospheric program. However, obtaining a suitable radiosonde sounding was not possible. The most appropriate one would have been at LaPaz, Bolivia, at the J. F. Kennedy International Airport which is at 13,398 feet. This airport is only a few miles from the lake and is located in the same weather system. The airport collects radiosonde data but not on a regular basis. According to the U.S. National Weather Service, January 29, 1974 was not one of those days. However, the National Weather Service did send data from the closest reporting station located in Chile, about 400 miles to the south. However, these data were not considered adequate.

The temperature of Lake Titicaca was monitored by a U.S. government team* at almost the precise time of S-191 overflight and was 13.5°C. Figure 25 shows the look position and time of S-191 data take at the lake. It also shows the position and time of the U.S. government team's temperature measurements.

Plots of all three of these data takes are shown in figures 26, 27, and 28. Additional atmospheric data is plotted in figure 26 on Monroe Reservoir and was provided through the courtesy of Dr. David C. Anding of Service Applications, Incorporated, in Ann Arbor, Michigan. His model input data was the same as in the Calfee-Pitts model, except that no ozone lines were assumed. The S-191 data was calculated with both the ambient and heated responsivities with the ambient calculation fitting the models best.

One anomaly is evident in the S-191 data and that is a broad and large absorption band centered at 9.4 μm. This band includes the ozone lines, but may be too broad to be ozone alone. This absorption band appears in the lunar data as well, where it had been theorized to be a Reststrahlen absorption band of a quartz-like constituent of the moon.

However, this absorption band may be partially instrument anomaly. The emissivity by the internal blackbody cal source coatings do not give any indication of absorption bands at 9.4 μm (ref 17, page 28). In addition, no silicon monoxide (which peaks around 9.4 μm) coating was applied to the external mirrors according to Block Engineering.

The lunar data indicated an increase in the absorption level of the band throughout the lunar data take. Between

*See appendix A.

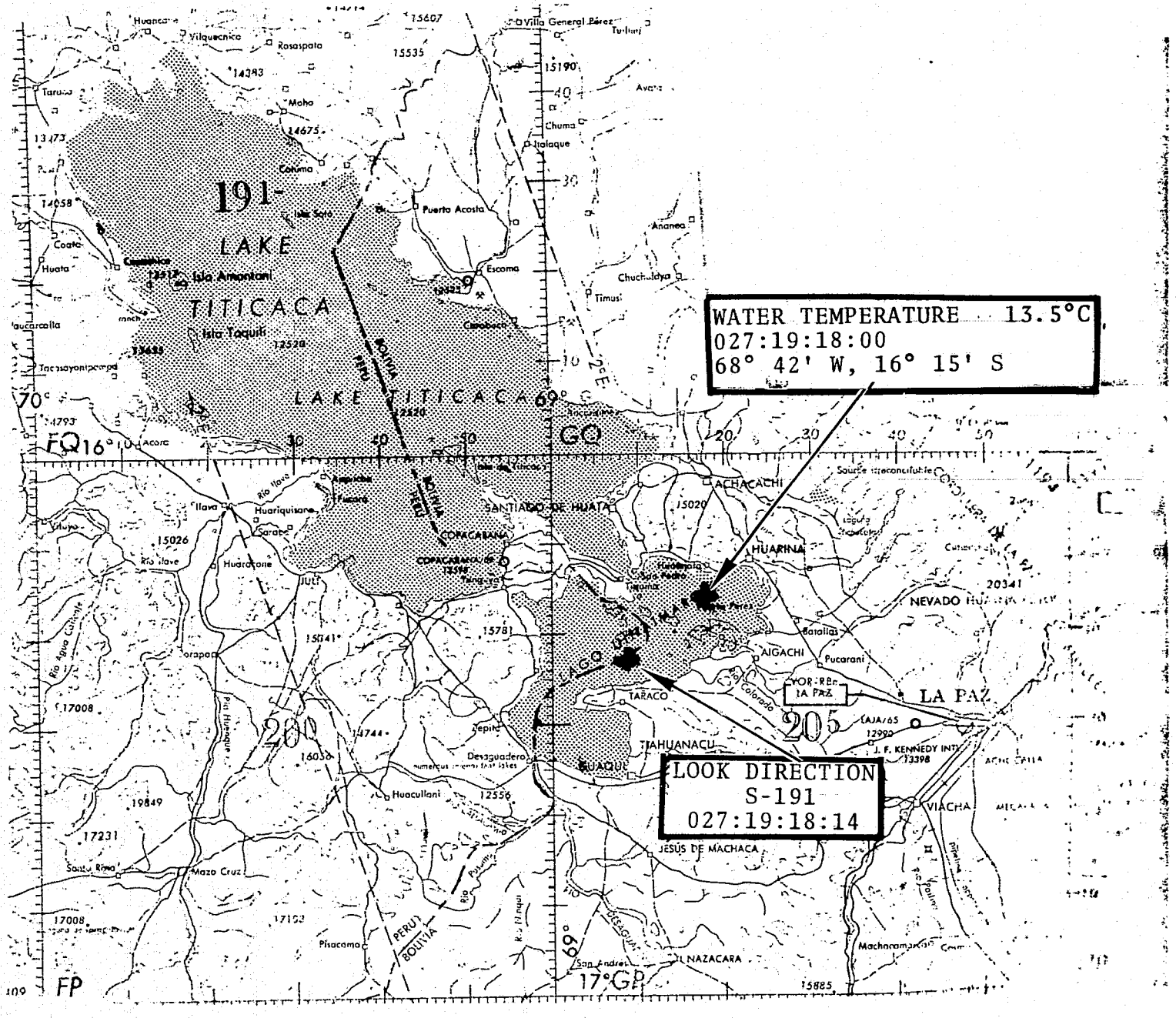
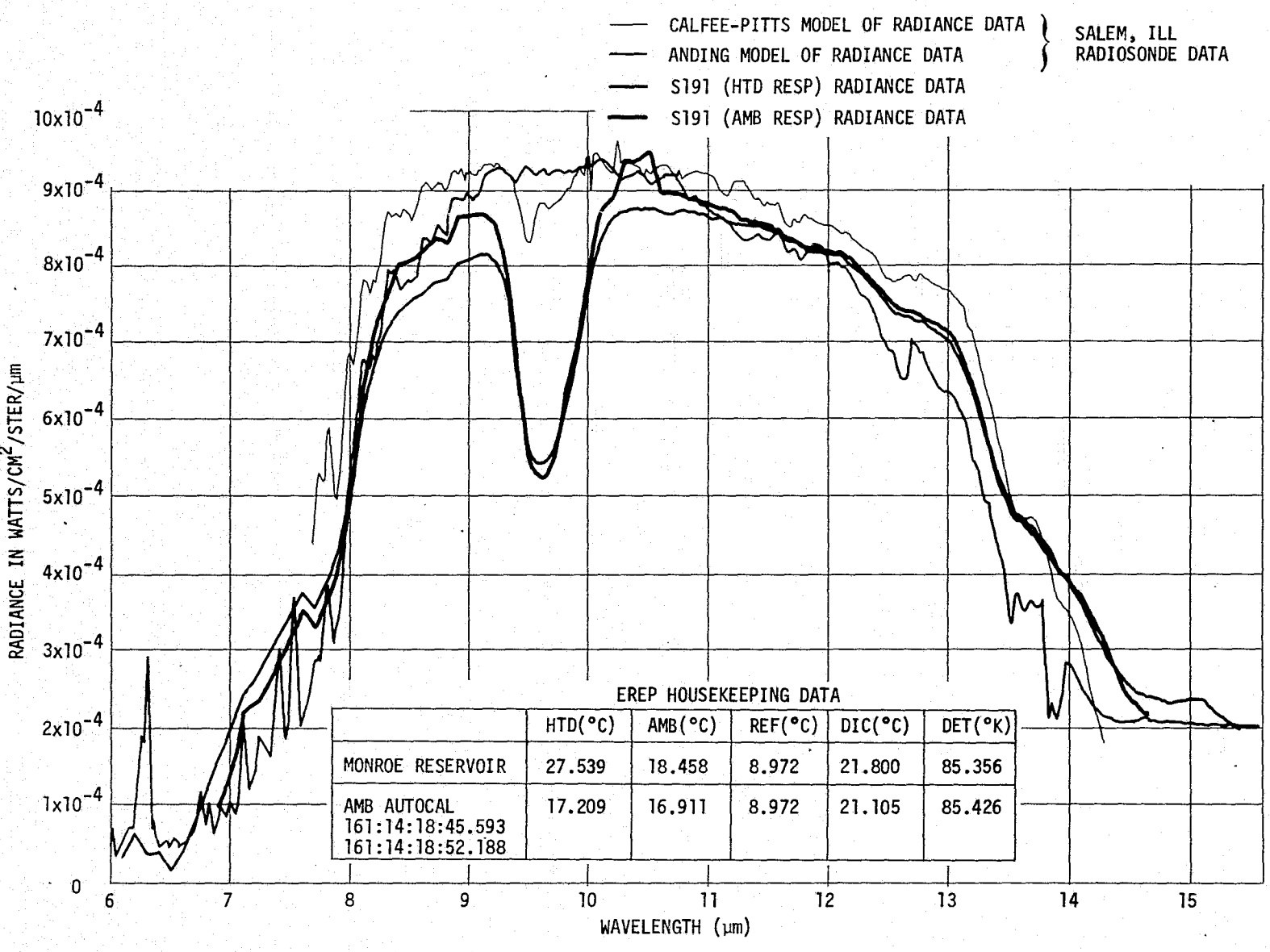



Figure 25. — Location of S-191 pointing direction and ground truth data collections.




EREP HOUSEKEEPING DATA

| | HTD(°C) | AMB(°C) | REF(°C) | DIC(°C) | DET(°K) |
|---|---|---|---|---|---|
| MONROE RESERVOIR | 27.539 | 18.458 | 8.972 | 21.800 | 85.356 |
| AMB AUTOCAL 161:14:18:45.593 161:14:18:52.188 | 17.209 | 16.911 | 8.972 | 21.105 | 85.426 |

Figure 26. — Comparison of S191 radiance data on Monroe Reservoir and radiance predictions by the Calfee-Pitts and Anding atmospheric models.

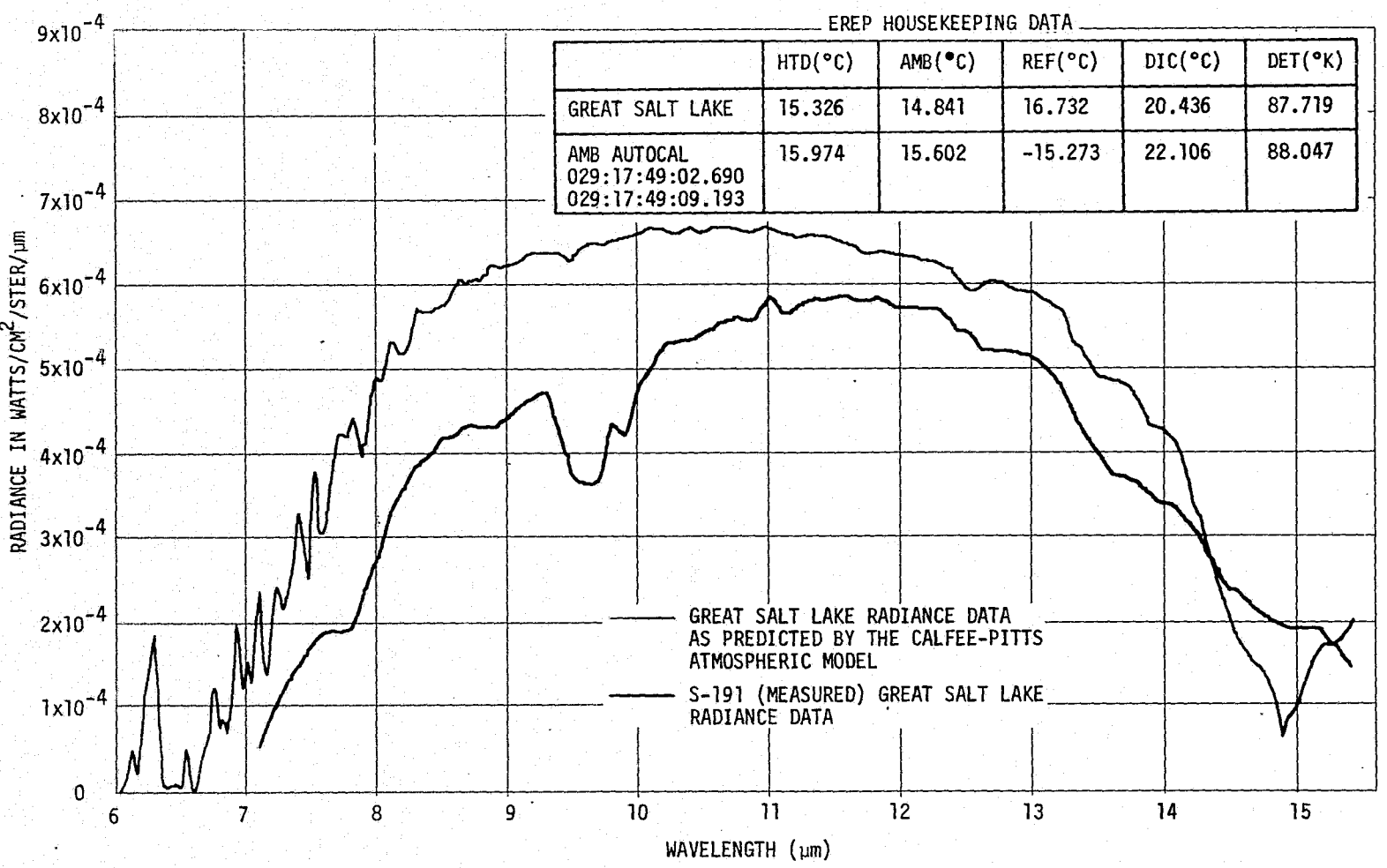



Figure 27. – Comparison of S191 radiance data on the Great Salt Lake and the radiance prediction by the Calfee-Pitts atmospheric model.

EREP HOUSEKEEPING DATA

| | HTD(°C) | AMB(°C) | REF(°C) | DIC(°C) | DET(°K) |
|---|---|---|---|---|---|
| LAKE TITICACA | 22.752 | 19.409 | 16.800 | 22.534 | 87.580 |
| AMB AUTOCAL<br>027:19:20:01.385<br>027:19:20:07.841 | 34.247 | 19.685 | -15.321 | 23.378 | 87.580 |

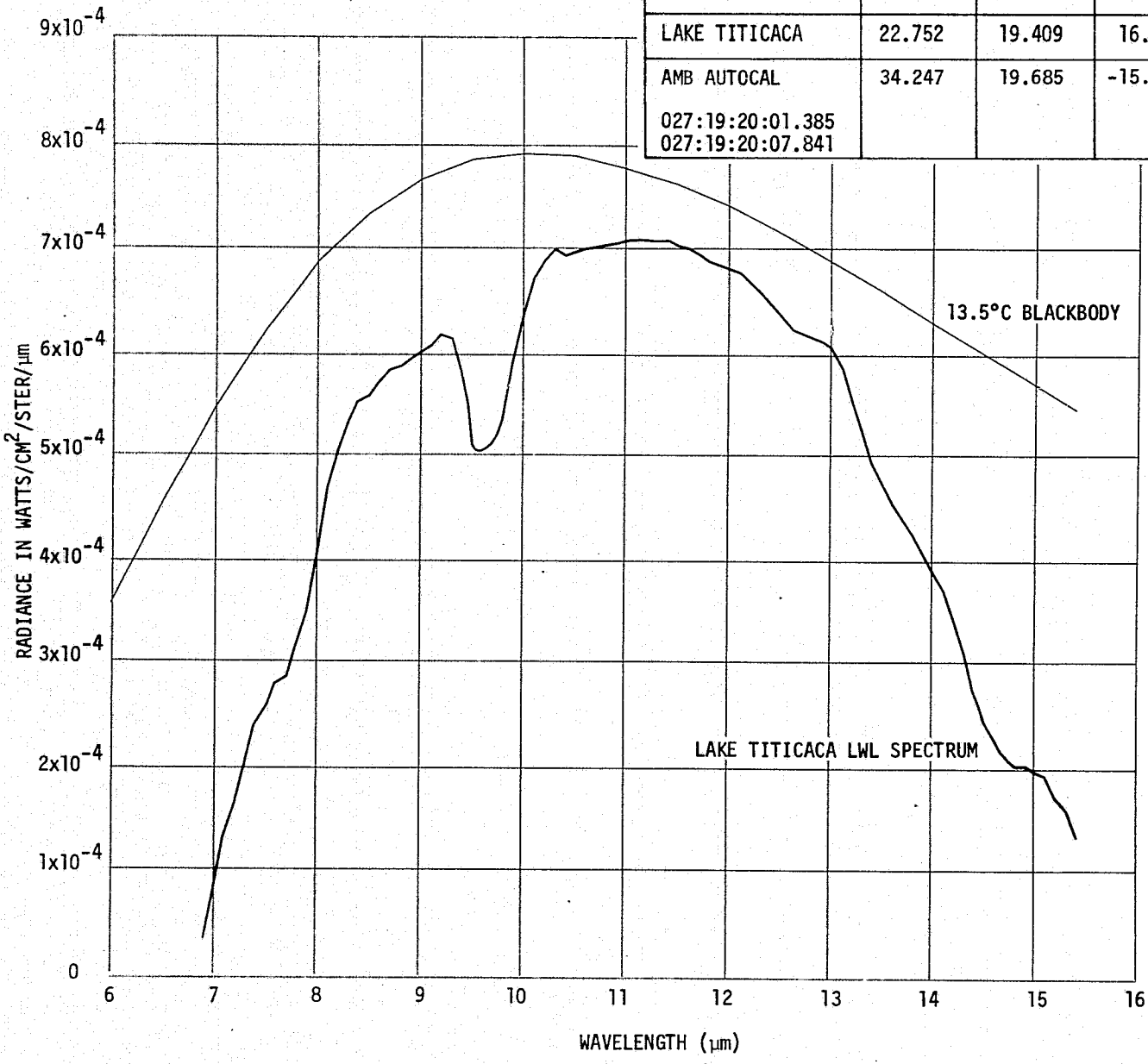



Figure 28. — Comparison of S-191 radiance data on Lake Titicaca and radiance from a 13.5°C blackbody.

ground calibration and DOY 161 (Monroe Reservoir data take), it is not known what type of contamination may have been applied to the external mirrors. It is suspected that contamination may be partially causing the absorption level whose peak occurs at 9.4 μm.

It should also be mentioned that Monroe Reservoir is the most optimum data take on any of the lake/reservoirs. The reference source temperature was not changed between auto cal and data take, and the ambient temperature of the cal source at 18.463°C was lower and close to that of the relatively warm reservoir at 25°C. In addition, S-191 data was taken very close to nadir and close to the beginning of the Skylab mission.

The data from the Great Salt Lake is shown in figure 27. S-191 data is approximately 10 percent lower than model prediction. It is not known what is causing these differences, however, the list of possible variables is quite long. These are:

1. The reference source setting during the auto cal was -15.242°C and 16.732°C during the data take.
2. The ambient source was 14.841°C and higher than the colder lake temperature of 5°C during data take. In addition, other instrument temperatures were quite high relative to lake temperature.
3. Detector temperature was high at 87.719°K during the data take.
4. Lake was about 10° off nadir during data take.
5. Weather conditions were poor, however, the lake was clearly visible in VTS imagery.

6. Progress of external mirror contamination was not known. It appears from lunar data that any data taken after DOY 343 may be quite marginal especially in the 9.4 μm region and deterioration at 10 through 11 μm became noticeable on DOY 007.

Additional data would be necessary to reduce the number of variables and identify the differences between the model prediction and the S-191 output.

The S-191 Lake Titicaca data is shown in figure 28 and does not show good agreement to a backbody curve at 13.5°C. A list of variables can also be developed:

1. The reference source setting during the auto cal was -15.353°C and 16.800°C during the data take.
2. The ambient temperature was 19.409°C, and the lake temperature was lower at 13.5°C during the data take. Additional temperatures within the instrument were higher than the lake temperature.
3. Lake was about 20° off nadir during data take.
4. Detector temperature was high at 87.580°C during data take.
5. Weather conditions were poor and cloudiness prevailed over the site.
6. Progress of S-191 external mirror contamination was not known.
7. The method of lake temperature monitoring is not known.

From this last data take, it would appear that direct calibration of instruments on high altitude lakes would not be possible without atmospheric programs.

## 4.0 CONCLUSION

In the shortwave length (SWL) portion of the spectrum, the repeatability of S-191 while viewing Mare Serenetatis was better than 5 percent for wavelengths .65 through .85 μm and 1.5 through 1.75 μm. All other wavelengths were better than 13 percent, except for the ends of the silicon band, .4 through .45 μm, and 1.05 through 1.10 μm. These wavelengths are generally unreliable in output.

An absolute calibration was made against the Backup-Unit while viewing the Lunar Mares. The most reliable measurements were made on Mare Serenetatis and compare within less than 13 percent overall at the wavelengths chosen for the backup unit calibration. DOY 254 (LC-3) and DOY 343 (LC-4) compare to within less than 5 percent to the backup unit data at the selected wavelengths.

The long wavelength (LWL) data on Mare Serenetatis is repeatable through DOY 343 (LC-4) between 8.5 and 14.5 μm to within 5 percent. On DOY 007 (LC-5), a serious absorption anomaly appeared and was centered at 9.4 μm. The band ends of the LWL from 6 through 8.5 μm and 14.5 through 15.4 μm appear to be affected by reference source setting. If the reference source setting is higher during data take than the auto cal, then the band ends of the radiance data tend to "roll up".

An absolute comparison was made between S-191 Lunar Mare data and that developed by Shorthill (ref 14). S-191 was calibrated using a responsivity calculated from the heated cal source. The heated cal source was about 50°C

(332°K) and was lower in apparent blackbody temperature than the moon, which is approximately 370 to 400°C. Comparison showed S-191 to be approximately 15 percent lower than Shorthill's measurements.

Additionally, S-191 lake and reservoir data was compared to atmospheric model data of these same lakes and reservoirs. These data comparisons were quite contradictory. Monroe Reservoir at close to ambient temperature (25°C) compared well with S-191 (except at the 9.4 μm absorption band) while the colder lakes did not.

The LWL data needs considerably more analysis before it can be better understood. Due to design shortcomings, and instrumentation shortcomings, it may never be possible to provide software fixes for a well calibrated output over the whole LWL band. The LWL deep space data may hold the key to improved instrument calibration.

## 5.0 REFERENCES


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# APPENDIX

## MEASUREMENTS TAKEN ON LAKE TITICACA IN SUPPORT OF SKYLAB EXPERIMENTS

OPTIONAL FORM NO. 10
MAY 1962 EDITION
GSA FPMR (41 CFR) 101-11.6

UNITED STATES GOVERNMENT

# *Memorandum*

TO : IAGS-P-A
ATTN : IAGS EROS Coordinator

**DATE:** 29 January 1974
IAGS-BOL/Mr. Allen

**FROM** : PD, IAGS-BOL

**SUBJECT:** Measurements taken on Lake Titicaca in support of SKYLAB experiments.

1. Reference: Memorandum, IAGS-EROS Training Coordinator, 13 July, 1973, subject as above.

2. Information requested in reference is provided below. A series of readings, bracketing the exact time of the pass were taken and all were constant.

3. Measurements taken on 27 January 1974, at 1918 GMT, 1518 Local time:

a. Water surface temperature----------13.5°C

b. Location----------68°42'W, 16°15'S

c. Air Temperature

(1) Wet Bulb----------54° Fahrenheit

(2) Dry Bulb----------70°Fahrenheit

d. Time----------1918 GMT

e. Cloud Cover----------4/10

f. Wind----------11KPH, 90°

g. Wave height----------20 cm.

JOHN W. FURRER
LTC, CE
Project Director

*Buy U.S. Savings Bonds Regularly on the Payroll Savings Plan*

# ADDENDUM

# TO

# S-191 SENSOR PERFORMANCE EVALUATION

LEC-5778

Dated June 1975

June 1975

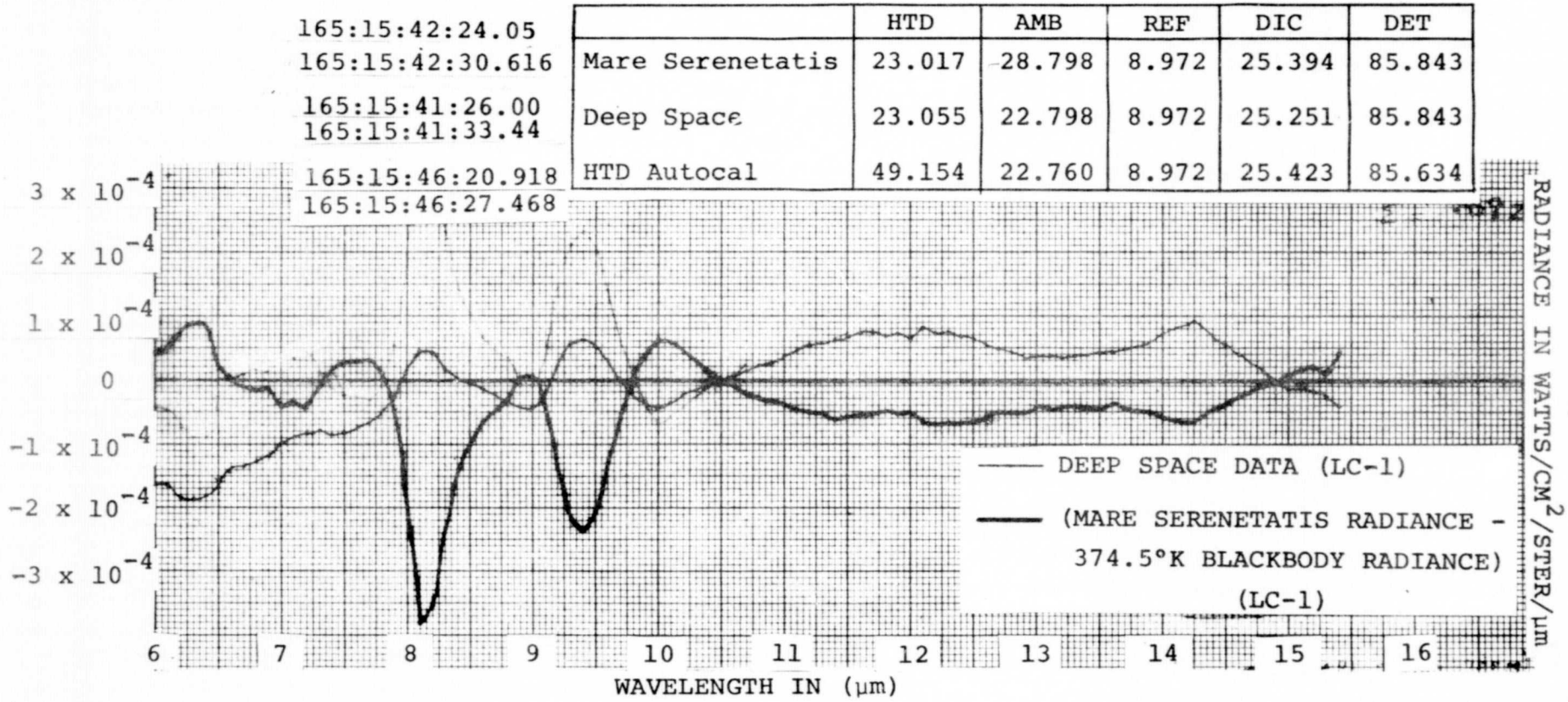
## Addendum

Further work on S-191 LWL data was carried out after the completion of the attached document. This work was concerned with reduction of data to determine what residual radiance the instrument was measuring when looking at deep space. In addition, an interpretation of this data relative to lunar data was desired.

One anomaly that was very prevalent in the Lunar data was a tendency to sag in the 11 through 15 μm band when compared to a blackbody curve (see figure 22 in the main text). Deep space data also had a tendency to zero at about 10.5 μm. For these reasons, it was decided to plot portions of a highly controlled data take during lunar calibration one (LC-1) when all data, i.e., autocal, lunar cal, and deep space were taken over a short time span (less than 6 minutes) at the same reference temperature 8.972°C. In order to compare Mare Serenetatis against deep space, a blackbody radiance curve was subtracted from Mare Serenetatis radiance data so that the difference would zero at 10.5 μm. The blackbody temperature satisfying this condition was at 374.5°K. The results are shown in figure 1.

This is a rather remarkable comparison, in that the 10 through 15.4 μm band appears like the outline of an ink blot in the Rorschach test in psychology.

Interpretation of this data can be made from the curves. The 10.5 through 14.8 μm range shows positive radiance for deep space and a negative radiance difference for Mare Serenetatis. Since responsivity calculations are very




| | HTD | AMB | REF | DIC | DET |
|---|---|---|---|---|---|
| Mare Serenetatis | 23.017 | 28.798 | 8.972 | 25.394 | 85.843 |
| Deep Space | 23.055 | 22.798 | 8.972 | 25.251 | 85.843 |
| HTD Autocal | 49.154 | 22.760 | 8.972 | 25.423 | 85.634 |

1. Both calculations made with HTD autocal responsitivities

2. Data takes and autocal had 8.972°C reference source temperature

Figure A-1.– Comparison of Mare Serenetatis against Deep Space.

nearly colinear for heated and ambient cal sources in this spectral region, the instrument is behaving nearly normal internally up to the external mirrors. The positive radiance for deep space would indicate a greater emissive property for the external mirrors than is developed in the radiance calculations. This is in keeping with previous assessments in the attached report, and may be caused by tarnishing or contamination on the external mirrors. (This is entirely possible since no known coatings were ever applied). The negative radiance difference for Mare Serenetatis minus the blackbody curve would therefore be caused by the extra emissive properties of the external mirror acting as an absorber for the "hotter" lunar radiance.

It is suspected that the moon acts very nearly like a blackbody, except at the 8.2 and 9.4 μm centered absorption bands which are real as no appreciable absorption occurs in these bands when the instrument looks at deep space.

The spectral regions from 6 through 10.5 μm and 14.8 through 15.4 μm have crossover points and these are caused by a combination of things, the mirror contaminant and improper modeling of the dichroic in the PHO-TR-524 equations (ref. 12).

Improper modeling of the dichroic has been investigated before, but only in the context of parametric studies on the PHO-TR-524 equations. These studies showed that responsivity colinearity (for ambient and heated autocal) could not be achieved by changes in the dichroic parameter values. What is being suggested here is that the equations be changed and

the instrument be re-modeled to account for dichroic transmission. In the present PHO-TR-524 equations, this is ignored. Transmission through the dichroic and dispersion of the energy out of the optical path would explain the higher responsitivities calculated for the heated cals at the band ends. The responsitivities which are nearly colinear could also be explained by the fact that the dichroic is acting close to the present model at some wavelengths.

Final Conclusions on LWL Data

Present users of LWL data must be wary of data at the band ends and also of data from subjects considerably different in temperature from that of the instrument. Deep space data should be especially avoided in any analysis without further instrument correction.

The S-191 output can be corrected to give more accurate readings on radiance data if further time and resources are alloted for its completion. This would not be possible except for a program (ref. 11) by E.L. Downes which would supply the software tools for this investigation.

The suggested procedure in this investigation would be to remodel the dichroic equations to account for transmission losses. The correctness of the model would be an iterative procedure in which the ambient and heated autocal responsitivities were colinearized. Next, deep space data would be used to properly determine the reflectance and emittance of the external mirrors. The adjusted model would then be used to test the lunar data for its closeness to a blackbody except for the known absorption bands.